NUTRIENTS/PESTICIDES

The fate and transport of nutrients and pesticides in a watershed depend on the transformations the compounds undergo in the soil environment. SWAT models the complete nutrient cycle for nitrogen and phosphorus as well as the degradation of any pesticides applied in an HRU.

The following three chapters review the methodology used by SWAT to simulate nutrient and pesticide processes in the soil.

CHAPTER 10

EQUATIONS: NITROGEN

The complexity of the nitrogen cycle and nitrogen's importance in plant growth have made this element the subject of much research. The nitrogen cycle is a dynamic system that includes the water, atmosphere and soil. Plants require nitrogen more than any other essential element, excluding carbon, oxygen and hydrogen.

10.1 NITROGEN CYCLE

The three major forms of nitrogen in mineral soils are organic nitrogen associated with humus, mineral forms of nitrogen held by soil colloids, and mineral forms of nitrogen in solution. Nitrogen may be added to the soil by fertilizer, manure or residue application, fixation by symbiotic or nonsymbiotic bacteria, and rain. Nitrogen is removed from the soil by plant uptake, leaching, volatilization, denitrification and erosion. Figure 10-1 shows the major components of the nitrogen cycle.
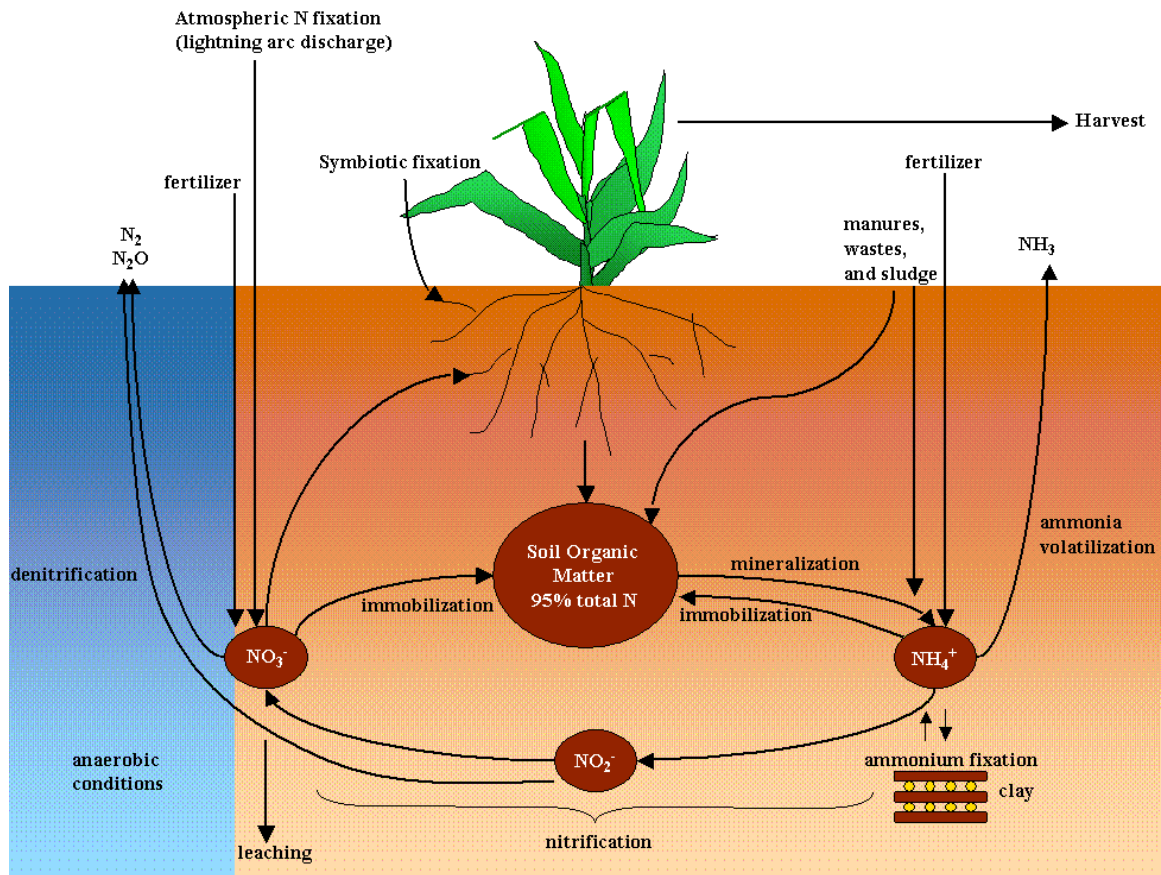
Figure 10-1: The nitrogen cycle

Nitrogen is considered to be an extremely reactive element. The highly reactive nature of nitrogen results from its ability to exist in a number of valance states. The valence state or oxidation state describes the number of electrons orbiting the nucleus of the nitrogen atom relative to the number present in an

electronically neutral atom. The valence state will be positive as the atom looses electrons and will be negative as the atom gains electrons. Examples of nitrogen in different valence states are:

most oxidized	+5	NO_3^-	nitrate
	+4	NO_2	nitrogen dioxide
	+3	NO_2^-	nitrite
	+2	NO	nitrogen monoxide (gas)
	+1	N_2O	nitrous oxide (laughing gas)
	0	N_2	N_2 gas or elemental N
	-1	NH_4OH	hydroxylamine
	-2	N_2H_4	hydrozine
most reduced	-3	NH_3 or NH_4^+	ammonia gas or ammonium

The ability of nitrogen to vary its valence state makes it a highly mobile element. Predicting the movement of nitrogen between the different pools in the soil is critical to the successful management of this element in the environment.

SWAT monitors five different pools of nitrogen in the soil (Figure 10-2). Two pools are inorganic forms of nitrogen, NH_4^+ and NO_3^-, while the other three pools are organic forms of nitrogen. Fresh organic N is associated with crop residue and microbial biomass while the active and stable organic N pools are associated with the soil humus. The organic nitrogen associated with humus is partitioned into two pools to account for the variation in availability of humic substances to mineralization.
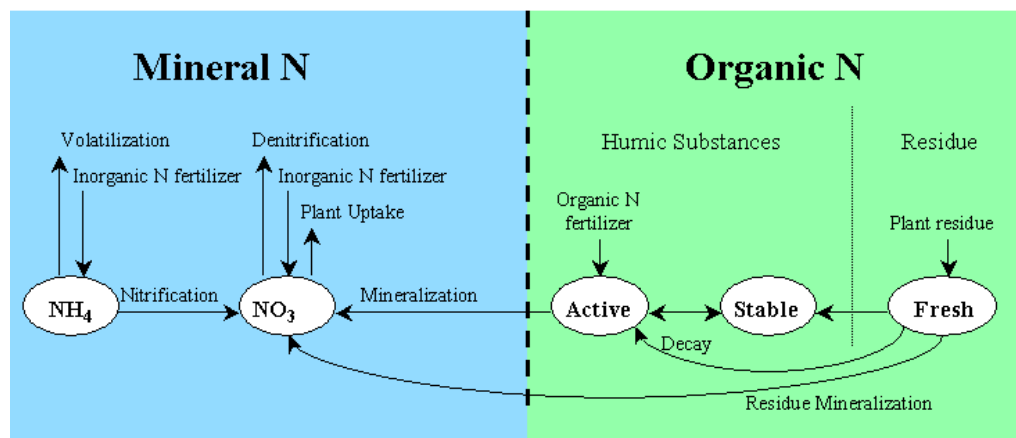
NITROGEN

Figure 10-2: SWAT soil nitrogen pools and processes that move nitrogen in and out of pools.

10.1.1 INITIALIZATION OF SOIL NITROGEN LEVELS

Users may define the amount of nitrate and organic nitrogen contained in humic substances for all soil layers at the beginning of the simulation. If the user does not specify initial nitrogen concentrations, SWAT will initialize levels of nitrogen in the different pools.

Initial nitrate levels in the soil are varied by depth using the relationship:

$$NO3_{conc,z} = 7 \cdot \exp\left(\frac{-z}{1000}\right)$$ 10.1.1

where $NO3_{conc,z}$ is the concentration of nitrate in the soil at depth z (mg/kg or ppm), and z is the depth from the soil surface (mm). The nitrate concentration with depth calculated from equation 10.1.1 is displayed in Figure 10-3. The nitrate concentration for a layer is calculated by solving equation 10.1.1 for the horizon's lower boundary depth.
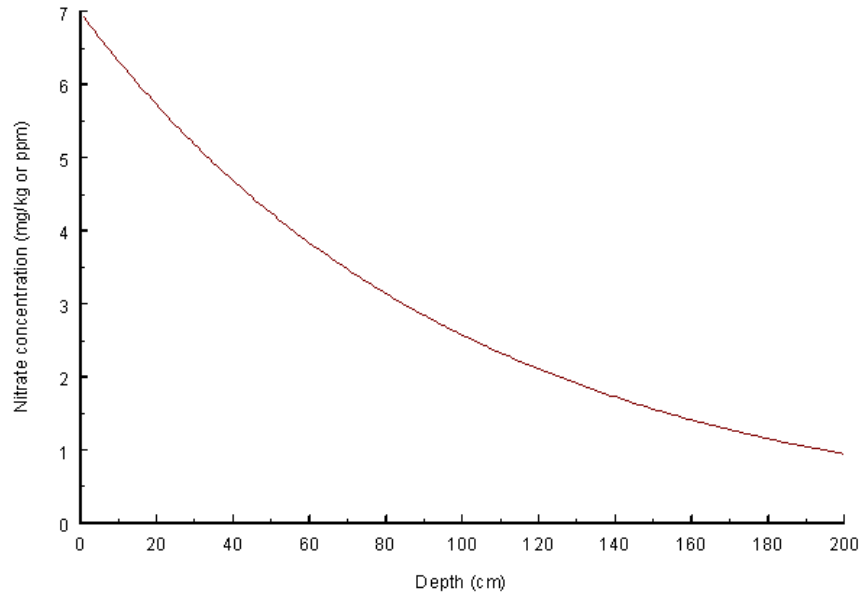

Figure 10-3: Nitrate concentration with depth.

Organic nitrogen levels are assigned assuming that the C:N ratio for humic materials is 14:1. The concentration of humic organic nitrogen in a soil layer is calculated:

$$orgN_{hum,ly} = 10^4 \cdot \left(\frac{orgC_{ly}}{14}\right)$$ 10.1.2

where $orgN_{hum,ly}$ is the concentration of humic organic nitrogen in the layer (mg/kg or ppm), and $orgC_{ly}$ is the amount of organic carbon in the layer (%). The humic organic N is partitioned between the active and stable pools using the following equations:

$$orgN_{act,ly} = orgN_{hum,ly} \cdot fr_{actN} \qquad 10.1.3$$

$$orgN_{sta,ly} = orgN_{hum,ly} \cdot (1 - fr_{actN}) \qquad 10.1.4$$

where $orgN_{act,ly}$ is the concentration of nitrogen in the active organic pool (mg/kg), $orgN_{hum,ly}$ is the concentration of humic organic nitrogen in the layer (mg/kg), fr_{actN} is the fraction of humic nitrogen in the active pool, and $orgN_{sta,ly}$ is the concentration of nitrogen in the stable organic pool (mg/kg). The fraction of humic nitrogen in the active pool, fr_{actN}, is set to 0.02.

Nitrogen in the fresh organic pool is set to zero in all layers except the top 10 mm of soil. In the top 10 mm, the fresh organic nitrogen pool is set to 0.15% of the initial amount of residue on the soil surface.

$$orgN_{frsh,surf} = 0.0015 \cdot rsd_{surf} \qquad 10.1.5$$

where $orgN_{frsh,surf}$ is the nitrogen in the fresh organic pool in the top 10 mm (kg N/ha), and rsd_{surf} is material in the residue pool for the top 10 mm of soil (kg/ha).

The ammonium pool for soil nitrogen, $NH4_{ly}$, is initialized to 0 ppm.

While SWAT allows nutrient levels to be input as concentrations, it performs all calculations on a mass basis. To convert a concentration to a mass, the concentration is multiplied by the bulk density and depth of the layer and divided by 100:

$$\frac{conc_N \cdot \rho_b \cdot depth_{ly}}{100} = \frac{\text{kg N}}{\text{ha}} \qquad 10.1.6$$

where $conc_N$ is the concentration of nitrogen in a layer (mg/kg or ppm), ρ_b is the bulk density of the layer (Mg/m^3), and $depth_{ly}$ is the depth of the layer (mm).

Table 10-1: SWAT input variables that pertain to nitrogen pools.

Variable Name	Definition	Input File
SOL_NO3	$NO3_{conc,ly}$: Initial NO_3 concentration in soil layer (mg/kg or ppm)	.chm
SOL_ORGN	$orgN_{hum,ly}$: Initial humic organic nitrogen in soil layer (mg/kg or ppm)	.chm
RSDIN	rsd_{surf}: Material in the residue pool for the top 10mm of soil (kg ha^{-1})	.hru
SOL_BD	ρ_b: Bulk density of the layer (Mg/m^3)	.sol
SOL_CBN	$orgC_{ly}$: Amount of organic carbon in the layer (%)	.sol

10.2 MINERALIZATION & DECOMPOSITION / IMMOBILIZATION

Decomposition is the breakdown of fresh organic residue into simpler organic components. Mineralization is the microbial conversion of organic, plant-unavailable nitrogen to inorganic, plant-available nitrogen. Immobilization is the microbial conversion of plant-available inorganic soil nitrogen to plant-unavailable organic nitrogen.

Bacteria decompose organic material to obtain energy for growth processes. Plant residue is broken down into glucose which is then converted to energy:

$$C_6H_{12}O_6 + O_2 \xrightarrow{\text{energy released}} 6CO_2 + 6H_2O$$
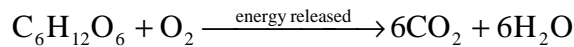
The energy released by the conversion of glucose to carbon dioxide and water is used for various cell processes, including protein synthesis. Protein synthesis requires nitrogen. If the residue from which the glucose is obtained contains enough nitrogen, the bacteria will use nitrogen from the organic material to meet the demand for protein synthesis. If the nitrogen content of the residue is too low to meet the bacterial demand for nitrogen, the bacteria will use NH_4^+ and NO_3^- from the soil solution to meet its needs. If the nitrogen content of the residue exceeds the bacterial demand for nitrogen, the bacterial will release the excess nitrogen into soil solution as NH_4^+. A general relationship between C:N ratio and mineralization/immobilization is:

C:N > 30:1   immobilization occurs, a net decrease in soil NH_4^+ and NO_3^-

20:1 ≤ C:N ≤ 30:1   expect no net change; immobilization and mineralization processes are at equilibrium

C:N < 20:1   mineralization occurs, a net gain in soil NH_4^+ and NO_3^-

The nitrogen mineralization algorithms in SWAT are **net** mineralization algorithms which incorporate immobilization into the equations. The algorithms were adapted from the PAPRAN mineralization model (Seligman and van Keulen, 1981). Two sources are considered for mineralization: the fresh organic N pool associated with crop residue and microbial biomass and the active organic N pool associated with soil humus. Mineralization and decomposition are allowed to occur only if the temperature of the soil layer is above 0°C.

Mineralization and decomposition are dependent on water availability and temperature. Two factors are used in the mineralization and decomposition equations to account for the impact of temperature and water on these processes.

The nutrient cycling temperature factor is calculated:

$$\gamma_{tmp,ly} = 0.9 \cdot \frac{T_{soil,ly}}{T_{soil,ly} + \exp\left[9.93 - 0.312 \cdot T_{soil,ly}\right]} + 0.1 \qquad 10.2.1$$

where $\gamma_{tmp,ly}$ is the nutrient cycling temperature factor for layer ly, and $T_{soil,ly}$ is the temperature of layer ly (°C). The nutrient cycling temperature factor is never allowed to fall below 0.1.

The nutrient cycling water factor is calculated:

$$\gamma_{sw,ly} = \frac{SW_{ly}}{FC_{ly}} \qquad 10.2.2$$

where $\gamma_{sw,ly}$ is the nutrient cycling water factor for layer ly, SW_{ly} is the water content of layer ly on a given day (mm H_2O), and FC_{ly} is the water content of layer ly at field capacity (mm H_2O). The nutrient cycling water factor is never allowed to fall below 0.05.

10.2.1 HUMUS MINERALIZATION

Nitrogen is allowed to move between the active and stable organic pools in the humus fraction. The amount of nitrogen transferred from one pool to the other is calculated:

$$N_{trns,ly} = \beta_{trns} \cdot orgN_{act,ly} \cdot \left(\frac{1}{fr_{actN}} - 1\right) - orgN_{sta,ly} \qquad 10.2.3$$

$N_{trns,ly}$ is the amount of nitrogen transferred between the active and stable organic pools (kg N/ha), β_{trns} is the rate constant (1×10^{-5}), $orgN_{act,ly}$ is the amount of nitrogen in the active organic pool (kg N/ha), fr_{actN} is the fraction of humic nitrogen in the active pool (0.02), and $orgN_{sta,ly}$ is the amount of nitrogen in the stable organic pool (kg N/ha). When $N_{trns,ly}$ is positive, nitrogen is moving from the active organic pool to the stable organic pool. When $N_{trns,ly}$ is negative, nitrogen is moving from the stable organic pool to the active organic pool.

Mineralization from the humus active organic N pool is calculated:

$$N_{mina,ly} = \beta_{min} \cdot \left(\gamma_{tmp,ly} \cdot \gamma_{sw,ly}\right)^{1/2} \cdot orgN_{act,ly} \qquad \text{10.2.4}$$

where $N_{mina,ly}$ is the nitrogen mineralized from the humus active organic N pool (kg N/ha), β_{min} is the rate coefficient for mineralization of the humus active organic nutrients, $\gamma_{tmp,ly}$ is the nutrient cycling temperature factor for layer ly, $\gamma_{sw,ly}$ is the nutrient cycling water factor for layer ly, $orgN_{act,ly}$ is the amount of nitrogen in the active organic pool (kg N/ha).

Nitrogen mineralized from the humus active organic pool is added to the nitrate pool in the layer.

10.2.2 RESIDUE DECOMPOSITION & MINERALIZATION

Decomposition and mineralization of the fresh organic nitrogen pool is allowed only in the first soil layer. Decomposition and mineralization are controlled by a decay rate constant that is updated daily. The decay rate constant is calculated as a function of the C:N ratio and C:P ratio of the residue, temperature and soil water content.

The C:N ratio of the residue is calculated:

$$\varepsilon_{C:N} = \frac{0.58 \cdot rsd_{ly}}{orgN_{frsh,ly} + NO3_{ly}} \qquad \text{10.2.5}$$

where $\varepsilon_{C:N}$ is the C:N ratio of the residue in the soil layer, rsd_{ly} is the residue in layer ly (kg/ha), 0.58 is the fraction of residue that is carbon, $orgN_{frsh,ly}$ is the nitrogen in the fresh organic pool in layer ly (kg N/ha), and $NO3_{ly}$ is the amount of nitrate in layer ly (kg N/ha).

The C:P ratio of the residue is calculated:

$$\varepsilon_{C:P} = \frac{0.58 \cdot rsd_{ly}}{orgP_{frsh,ly} + P_{solution,ly}}$$ 10.2.6

where $\varepsilon_{C:P}$ is the C:P ratio of the residue in the soil layer, rsd_{ly} is the residue in layer ly (kg/ha), 0.58 is the fraction of residue that is carbon, $orgP_{frsh,ly}$ is the phosphorus in the fresh organic pool in layer ly (kg P/ha), and $P_{solution,ly}$ is the amount of phosphorus in solution in layer ly (kg P/ha).

The decay rate constant defines the fraction of residue that is decomposed. The decay rate constant is calculated:

$$\delta_{ntr,ly} = \beta_{rsd} \cdot \gamma_{ntr,ly} \cdot \left(\gamma_{tmp,ly} \cdot \gamma_{sw,ly}\right)^{1/2}$$ 10.2.7

where $\delta_{ntr,ly}$ is the residue decay rate constant, β_{rsd} is the rate coefficient for mineralization of the residue fresh organic nutrients, $\gamma_{ntr,ly}$ is the nutrient cycling residue composition factor for layer ly, $\gamma_{tmp,ly}$ is the nutrient cycling temperature factor for layer ly, and $\gamma_{sw,ly}$ is the nutrient cycling water factor for layer ly.

The nutrient cycling residue composition factor is calculated:

$$\gamma_{ntr,ly} = \min \begin{cases} \exp\left[-0.693 \cdot \dfrac{(\varepsilon_{C:N} - 25)}{25}\right] \\[2mm] \exp\left[-0.693 \cdot \dfrac{(\varepsilon_{C:P} - 200)}{200}\right] \\[2mm] 1.0 \end{cases}$$ 10.2.8

where $\gamma_{ntr,ly}$ is the nutrient cycling residue composition factor for layer ly, $\varepsilon_{C:N}$ is the C:N ratio on the residue in the soil layer, and $\varepsilon_{C:P}$ is the C:P ratio on the residue in the soil layer.

Mineralization from the residue fresh organic N pool is then calculated:

$$N_{minf,ly} = 0.8 \cdot \delta_{ntr,ly} \cdot orgN_{frsh,ly}$$ 10.2.9

where $N_{minf,ly}$ is the nitrogen mineralized from the fresh organic N pool (kg N/ha), $\delta_{ntr,ly}$ is the residue decay rate constant, and $orgN_{frsh,ly}$ is the nitrogen in the fresh organic pool in layer ly (kg N/ha). Nitrogen mineralized from the fresh organic pool is added to the nitrate pool in the layer.

Decomposition from the residue fresh organic N pool is calculated:

$$N_{dec,ly} = 0.2 \cdot \delta_{ntr,ly} \cdot orgN_{frsh,ly}$$ 10.2.9
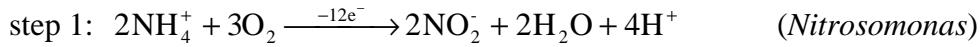
where $N_{dec,ly}$ is the nitrogen decomposed from the fresh organic N pool (kg N/ha), $\delta_{ntr,ly}$ is the residue decay rate constant, and $orgN_{frsh,ly}$ is the nitrogen in the fresh organic pool in layer ly (kg N/ha). Nitrogen decomposed from the fresh organic pool is added to the humus active organic pool in the layer.

Table 10-2: SWAT input variables that pertain to mineralization.

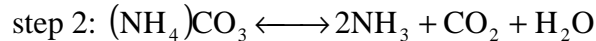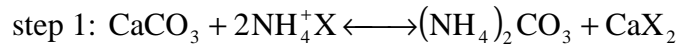| Variable Name	Definition	Input File
CMN	β_{min}: Rate coefficient for mineralization of the humus active organic nutrients	.bsn
RSDCO	β_{rsd}: Rate coefficient for mineralization of the residue fresh organic nutrients	.bsn
RSDCO_PL	β_{rsd}: Rate coefficient for mineralization of the residue fresh organic nutrients	crop.dat

10.3 NITRIFICATION & AMMONIA VOLATILIZATION

Nitrification is the two-step bacterial oxidation of NH_4^+ to NO_3^-.

step 1: $2NH_4^+ + 3O_2 \xrightarrow{-12e^-} 2NO_2^- + 2H_2O + 4H^+$ (*Nitrosomonas*)

step 2: $2NO_2^- + O_2 \xrightarrow{-4e^-} 2NO_3^-$ (*Nitrobacter*)
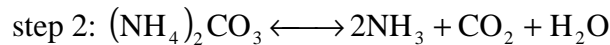
Ammonia volatilization is the gaseous loss of NH_3 that occurs when ammonium, NH_4^+, is surface applied to a calcareous soil or when urea, $(NH_2)_2CO$, is surface applied to any soil.

NH_4^+ surface applied to a calcareous soil:

step 1: $CaCO_3 + 2NH_4^+X \longleftrightarrow (NH_4)_2CO_3 + CaX_2$

step 2: $(NH_4)CO_3 \longleftrightarrow 2NH_3 + CO_2 + H_2O$

Urea surface applied to any soil:

step 1: $(NH_2)_2CO + 2H_2O \xleftrightarrow{\text{urease enzyme}} (NH_4)_2CO_3$

step 2: $(NH_4)_2CO_3 \longleftrightarrow 2NH_3 + CO_2 + H_2O$
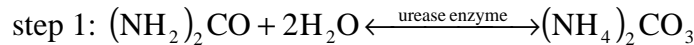
SWAT simulates nitrification and ammonia volatilization using a combination of the methods developed by Reddy et al. (1979) and Godwin et al. (1984). The total amount of nitrification and ammonia volatilization is calculated, and then partitioned between the two processes. Nitrification is a function of soil

temperature and soil water content while ammonia volatilization is a function of soil temperature and depth. Three coefficients are used in the nitrification/volatilization algorithms to account for the impact of these parameters. Nitrification/volatilization occurs only when the temperature of the soil layer exceeds 5°C.

The nitrification/volatilization temperature factor is calculated:

$$\eta_{tmp,ly} = 0.41 \cdot \frac{(T_{soil,ly} - 5)}{10} \qquad \text{if } T_{soil,ly} > 5 \qquad \qquad 10.3.1$$

where $\eta_{tmp,ly}$ is the nitrification/volatilization temperature factor, and $T_{soil,ly}$ is the temperature of layer ly (°C).

The nitrification soil water factor is calculated:

$$\eta_{sw,ly} = \frac{SW_{ly} - WP_{ly}}{0.25 \cdot (FC_{ly} - WP_{ly})} \quad \text{if } SW_{ly} - WP_{ly} < 0.25 \cdot (FC_{ly} - WP_{ly}) \quad 10.3.2$$

$$\eta_{sw,ly} = 1.0 \qquad \qquad \text{if } SW_{ly} - WP_{ly} \geq 0.25 \cdot (FC_{ly} - WP_{ly}) \quad 10.3.3$$

where $\eta_{sw,ly}$ is the nitrification soil water factor, SW_{ly} is the soil water content of layer ly on a given day (mm H_2O), WP_{ly} is the amount of water held in the soil layer at wilting point water content (mm H_2O), and FC_{ly} is the amount of water held in the soil layer at field capacity water content (mm H_2O).

The volatilization depth factor is calculated:

$$\eta_{midz,ly} = 1 - \frac{z_{mid,ly}}{z_{mid,ly} + \exp[4.706 - 0.305 \cdot z_{mid,ly}]} \qquad 10.3.4$$

where $\eta_{midz,ly}$ is the volatilization depth factor, and $z_{mid,ly}$ is the depth from the soil surface to the middle of the layer (mm).

The impact of environmental factors on nitrification and ammonia volatilization in a given layer is defined by the nitrification regulator and volatilization regulator. The nitrification regulator is calculated:

$$\eta_{nit,ly} = \eta_{tmp,ly} \cdot \eta_{sw,ly} \qquad \qquad 10.3.5$$

and the volatilization regulator is calculated:

$$\eta_{vol,ly} = \eta_{tmp,ly} \cdot \eta_{midz,ly} \qquad \qquad 10.3.6$$

where $\eta_{nit,ly}$ is the nitrification regulator, $\eta_{vol,ly}$ is the volatilization regulator, $\eta_{tmp,ly}$ is the nitrification/volatilization temperature factor, $\eta_{sw,ly}$ is the nitrification soil water factor, and $\eta_{midz,ly}$ is the volatilization depth factor.

The total amount of ammonium lost to nitrification and volatilization is calculated using a first-order kinetic rate equation (Reddy et al., 1979):

$$N_{nit|vol,ly} = NH4_{ly} \cdot \left(1 - \exp\left[-\eta_{nit,ly} - \eta_{vol,ly}\right]\right)$$ 10.3.7

where $N_{nit|vol,ly}$ is the amount of ammonium converted via nitrification and volatilization in layer ly (kg N/ha), $NH4_{ly}$ is the amount of ammonium in layer ly (kg N/ha), $\eta_{nit,ly}$ is the nitrification regulator, and $\eta_{vol,ly}$ is the volatilization regulator.

To partition $N_{nit|vol,ly}$ between nitrification and volatilization, the expression by which $NH4_{ly}$ is multiplied in equation 10.3.7, is solved using each regulator individually to obtain a fraction of ammonium removed by each process:

$$fr_{nit,ly} = 1 - \exp\left[-\eta_{nit,ly}\right]$$ 10.3.8

$$fr_{vol,ly} = 1 - \exp\left[-\eta_{vol,ly}\right]$$ 10.3.9

where $fr_{nit,ly}$ is the estimated fraction of nitrogen lost by nitrification, $fr_{vol,ly}$ is the estimated fraction of nitrogen lost by volatilization, $\eta_{nit,ly}$ is the nitrification regulator, and $\eta_{vol,ly}$ is the volatilization regulator.

The amount of nitrogen removed from the ammonium pool by nitrification is then calculated:

$$N_{nit,ly} = \frac{fr_{nit,ly}}{\left(fr_{nit,ly} + fr_{vol,ly}\right)} \cdot N_{nit|vol,ly}$$ 10.3.10

and the amount of nitrogen removed from the ammonium pool by volatilization is:

$$N_{vol,ly} = \frac{fr_{vol,ly}}{\left(fr_{nit,ly} + fr_{vol,ly}\right)} \cdot N_{nit|vol,ly}$$ 10.3.11

where $N_{nit,ly}$ is the amount of nitrogen converted from NH_4^+ to NO_3^- in layer ly (kg N/ha), $N_{vol,ly}$ is the amount of nitrogen converted from NH_4^+ to NH_3 in layer ly (kg

N/ha), $fr_{nit,ly}$ is the estimated fraction of nitrogen lost by nitrification, $fr_{vol,ly}$ is the estimated fraction of nitrogen lost by volatilization, and $N_{nit|vol,ly}$ is the amount of ammonium converted via nitrification and volatilization in layer ly (kg N/ha)

10.4 DENITRIFICATION

Denitrification is the bacterial reduction of nitrate, NO_3^-, to N_2 or N_2O gases under anaerobic (reduced) conditions. Denitrification is a function of water content, temperature, presence of a carbon source and nitrate.

In general, when the water-filled porosity is greater than 60% denitrification will be observed in a soil. As soil water content increases, anaerobic conditions develop due to the fact that oxygen diffuses through water 10,000 times slower than through air. Because the rate of oxygen diffusion through water slows as the water temperature increases, temperature will also influence denitrification.

Cropping systems where water is ponded, such as rice, can lose a large fraction of fertilizer by denitrification. For a regular cropping system, an estimated 10-20% of nitrogen fertilizer may be lost to denitrification. Under a rice cropping system, 50% of nitrogen fertilizer may be lost to denitrification. In a flooded cropping system, the depth of water plays an important role because it controls the amount of water oxygen has to diffuse through to reach the soil.

SWAT determines the amount of nitrate lost to denitrification with the equation:

$$N_{denit,ly} = NO3_{ly} \cdot \left(1 - \exp\left[-1.4 \cdot \gamma_{tmp,ly} \cdot orgC_{ly}\right]\right) \quad \text{if } \gamma_{sw,ly} \geq 0.95 \qquad 10.4.1$$

$$N_{denit,ly} = 0.0 \qquad\qquad\qquad\qquad\qquad\qquad\qquad \text{if } \gamma_{sw,ly} < 0.95 \qquad 10.4.2$$

where $N_{denit,ly}$ is the amount of nitrogen lost to denitrification (kg N/ha), $NO3_{ly}$ is the amount of nitrate in layer ly (kg N/ha), $\gamma_{tmp,ly}$ is the nutrient cycling temperature factor for layer ly calculated with equation 10.2.1, $\gamma_{sw,ly}$ is the nutrient cycling water factor for layer ly calculated with equation 10.2.2, $orgC_{ly}$ is the amount of organic carbon in the layer (%).

Table 10-3: SWAT input variables that pertain to denitrification.

Variable Name	Definition	Input File
SOL_CBN	$orgC_{ly}$: Amount of organic carbon in the layer (%)	.sol

10.5 NITROGEN IN RAINFALL

Lightning discharge converts atmospheric N_2 to nitric acid which can then be transferred to the soil with precipitation. The chemical steps involved are:

step 1: $N_2 + O_2 \xrightarrow{\text{arc of electricity}} 2NO$ (monoxide)

step 2: $2NO + O_2 \longrightarrow NO_2$ (dioxide)

step 3: $3NO_2 + H_2O \longrightarrow 2HNO_2 + NO$ (nitric acid and monoxide)

More nitrogen will be added to the soil with rainfall in areas with a high amount of lightning activity than in areas with little lightning.

The amount of nitrate added to the soil in rainfall is calculated:

$$N_{rain} = 0.01 \cdot R_{NO3} \cdot R_{day} \qquad\qquad 10.5.1$$

where N_{rain} is nitrate added by rainfall (kg N/ha), R_{NO3} is the concentration of nitrogen in the rain (mg N/L), and R_{day} is the amount of precipitation on a given day (mm H_2O). The nitrogen in rainfall is added to the nitrate pool in the top 10 mm of soil.

Table 10-4: SWAT input variables that pertain to nitrogen in rainfall.

Variable Name	Definition	Input File
RCN	R_{NO3}: Concentration of nitrogen in the rain (mg N/L)	.bsn

10.6 FIXATION

Legumes are able to obtain a portion of their nitrogen demand through fixation of atmospheric N_2 performed by rhizobia living in association with the plant. In exchange for nitrogen, the plant supplies the bacteria with carbohydrates.

SWAT simulates nitrogen fixation by legumes when the soil does not supply the plant with the amount of nitrogen needed for growth. The nitrogen obtained by fixation is incorporated directly into the plant biomass and never enters the soil (unless plant biomass is added to the soil as residue after the plant

is killed). The equations for nitrogen fixation by legumes are reviewed in Chapter 18.

10.7 UPWARD MOVEMENT OF NITRATE IN WATER

As water evaporates from the soil surface, the water content at the surface drops, creating a gradient in the profile. Water from lower in the profile will move upward in response to the gradient, carrying dissolved nutrients with it. SWAT allows nitrate to be transported from the first soil layer defined in the .sol file to the surface top 10 mm of soil with the equation:

$$N_{evap} = 0.1 \cdot NO3_{ly} \cdot \frac{E''_{soil,ly}}{SW_{ly}}$$

where N_{evap} is the amount of nitrate moving from the first soil layer to the soil surface zone (kg N/ha), $NO3_{ly}$ is the nitrate content of the first soil layer (kg N/ha), $E''_{soil,ly}$ is the amount of water removed from the first soil layer as a result of evaporation (mm H_2O), and SW_{ly} is the soil water content of the first soil layer (mm H_2O).

10.8 LEACHING

The majority of plant-essential nutrients are cations which are attracted and sorbed to negatively-charged soil particles. As plants extract these cations from soil solution, the soil particles release bound cations into soil solution to bring the ratio of nutrients in solution and on soil particles back into equilibrium. In effect, the soil buffers the concentration of cations in solution.

In contrast, nitrate is an anion and is not attracted to or sorbed by soil particles. Because retention of nitrate by soils is minimal, nitrate is very susceptible to leaching. The algorithms used by SWAT to calculated nitrate leaching simultaneously solve for loss of nitrate in surface runoff and lateral flow also. These algorithms are reviewed in Chapter 14.

10.9 NOMENCLATURE

$E''_{soil,ly}$ Amount of water removed from layer ly by evaporation (mm H_2O)

FC_{ly} Water content of layer ly at field capacity (mm H_2O)

$N_{dec,ly}$ Nitrogen decomposed from the fresh organic N pool (kg N/ha)

$N_{denit,ly}$ Amount of nitrogen lost to denitrification (kg N/ha)

N_{evap} Amount of nitrate moving from the first soil layer to the soil surface zone (kg N/ha)

$N_{mina,ly}$ Nitrogen mineralized from the humus active organic N pool (kg N/ha)

$N_{minf,ly}$ Nitrogen mineralized from the fresh organic N pool (kg N/ha)

$N_{nit,ly}$ Amount of nitrogen converted from NH_4^+ to NO_3^- in layer ly (kg N/ha)

$N_{nit|vol,ly}$ Amount of ammonium converted via nitrification and volatilization in layer ly (kg N/ha)

N_{rain} Nitrate added by rainfall (kg N/ha)

$N_{trns,ly}$ Amount of nitrogen transferred between the active and stable organic pools (kg N/ha)

$N_{vol,ly}$ Amount of nitrogen converted from NH_4^+ to NH_3 in layer ly (kg N/ha)

$NH4_{ly}$ Ammonium content of layer ly (kg NH_4-N/ha)

$NO3_{conc,z}$ Concentration of nitrate in the soil at depth z (mg/kg or ppm)

$NO3_{ly}$ Nitrate content of soil layer ly (kg NO_3-N/ha)

$P_{solution,ly}$ Solution phosphorus content of soil layer ly (kg P/ha)

R_{day} Amount of rainfall on a given day (mm H_2O)

R_{NO3} Concentration of nitrogen in the rain (mg N/L)

SW_{ly} Soil water content of layer ly (mm H_2O)

$T_{soil,ly}$ Temperature of layer ly (°C)

WP_{ly} Water content of layer ly at wilting point (mm H_2O)

$conc_N$ Concentration of nitrogen in a layer (mg/kg or ppm)

$depth_{ly}$ Depth of the layer (mm)

fr_{actN} Fraction of humic nitrogen in the active pool

$fr_{nit,ly}$ Estimated fraction of nitrogen lost by nitrification

$fr_{vol,ly}$ Estimated fraction of nitrogen lost by volatilization

$orgC_{ly}$ Amount of organic carbon in the layer (%)

$orgN_{act,ly}$ Nitrogen in the active organic pool in layer ly (mg/kg or kg N/ha)

$orgN_{frsh,ly}$ Nitrogen in the fresh organic pool in layer ly (kg N/ha)

$orgN_{hum,ly}$ Concentration of humic organic nitrogen in the layer (mg/kg or ppm)

$orgN_{sta,ly}$ Nitrogen in the stable organic pool in layer ly (mg/kg or kg N/ha)

$orgP_{frsh,ly}$ Phosphorus in the fresh organic pool in layer ly (kg P/ha)

rsd_{ly} Residue in layer ly (kg/ha)

z Depth below soil surface (mm)

$z_{mid,ly}$ Depth from the soil surface to the middle of the layer (mm)

β_{min} Rate coefficient for mineralization of the humus active organic nutrients

β_{rsd} Rate coefficient for mineralization of the residue fresh organic nutrients

β_{trns} Rate constant for nitrogen transfer between active and stable organic pools (1×10^{-5})

$\delta_{ntr,ly}$ Residue decay rate constant

$\varepsilon_{C:N}$ Residue C:N ratio in the soil layer

$\varepsilon_{C:P}$ Residue C:P ratio in the soil layer

$\gamma_{ntr,ly}$ Nutrient cycling residue composition factor for layer *ly*

$\gamma_{sw,ly}$ Nutrient cycling water factor for layer *ly*

$\gamma_{tmp,ly}$ Nutrient cycling temperature factor for layer *ly*

$\eta_{midz,ly}$ Volatilization depth factor

$\eta_{nit,ly}$ Nitrification regulator

$\eta_{sw,ly}$ Nitrification soil water factor

$\eta_{tmp,ly}$ Nitrification/volatilization temperature factor

$\eta_{vol,ly}$ Volatilization regulator

ρ_b Bulk density of the layer (Mg/m^3)

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CHAPTER 11

EQUATIONS: PHOSPHORUS

Although plant phosphorus demand is considerably less than nitrogen demand, phosphorus is required for many essential functions. The most important of these is its role in energy storage and transfer. Energy obtained from photosynthesis and metabolism of carbohydrates is stored in phosphorus compounds for later use in growth and reproductive processes.

11.1 PHOSPHORUS CYCLE

The three major forms of phosphorus in mineral soils are organic phosphorus associated with humus, insoluble forms of mineral phosphorus, and plant-available phosphorus in soil solution. Phosphorus may be added to the soil by fertilizer, manure or residue application. Phosphorus is removed from the soil by plant uptake and erosion. Figure 11-1 shows the major components of the phosphorus cycle.

Figure 11-1: The phosphorus cycle
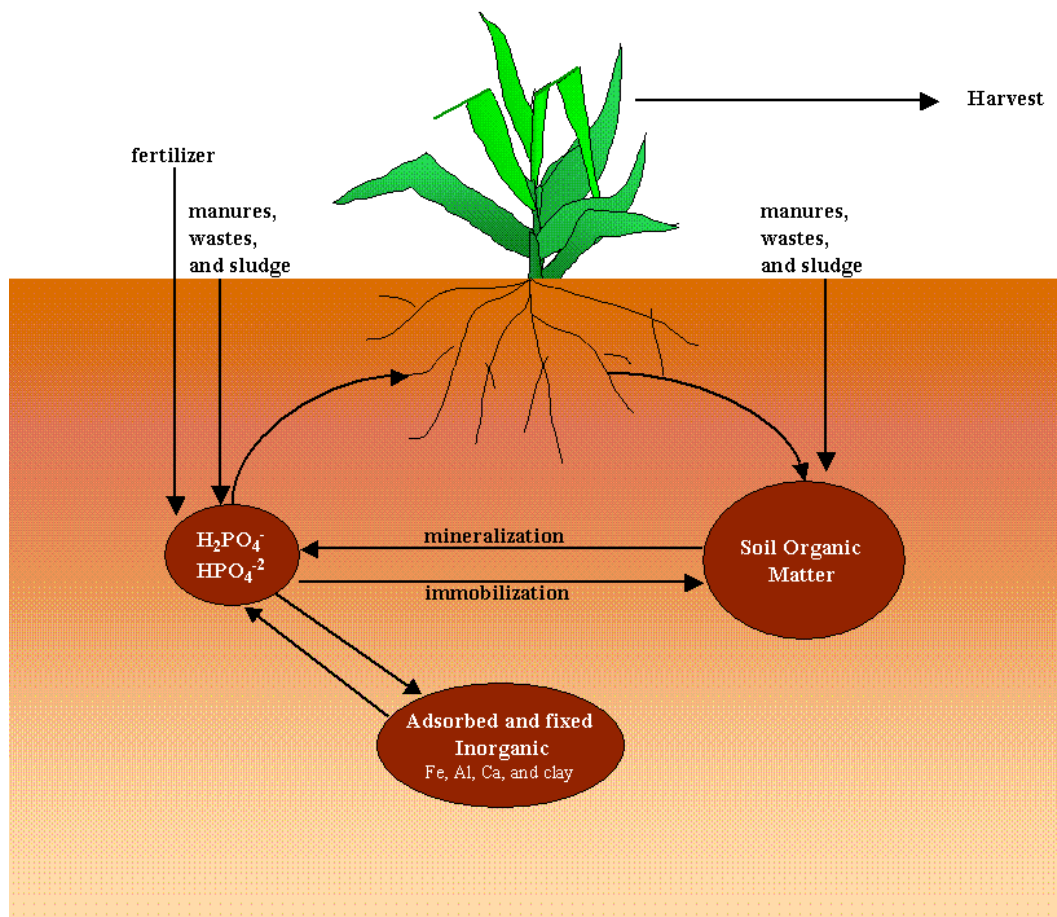
Unlike nitrogen which is highly mobile, phosphorus solubility is limited in most environments. Phosphorus combines with other ions to form a number of insoluble compounds that precipitate out of solution. These characteristics contribute to a build-up of phosphorus near the soil surface that is readily available for transport in surface runoff. Sharpley and Syers (1979) observed that

surface runoff is the primary mechanism by which phosphorus is exported from most catchments.

SWAT monitors six different pools of phosphorus in the soil (Figure 11-2). Three pools are inorganic forms of phosphorus while the other three pools are organic forms of phosphorus. Fresh organic P is associated with crop residue and microbial biomass while the active and stable organic P pools are associated with the soil humus. The organic phosphorus associated with humus is partitioned into two pools to account for the variation in availability of humic substances to mineralization. Soil inorganic P is divided into solution, active, and stable pools. The solution pool is in rapid equilibrium (several days or weeks) with the active pool. The active pool is in slow equilibrium with the stable pool.
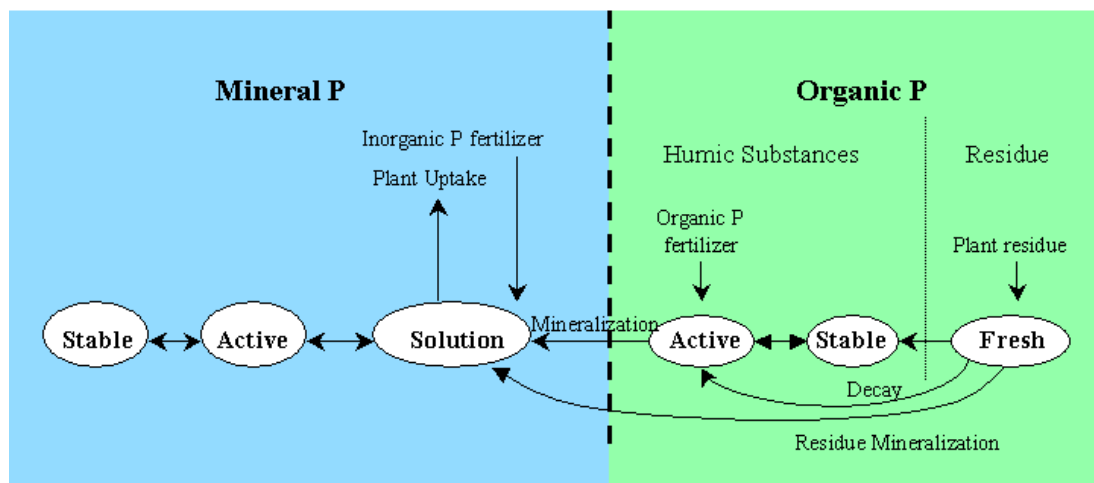
PHOSPHORUS

Figure 11-2: SWAT soil phosphorus pools and processes that move P in and out of pools.

11.1.1 INITIALIZATION OF SOIL PHOSPHORUS LEVELS

Users may define the amount of soluble P and organic phosphorus contained in humic substances for all soil layers at the beginning of the simulation. If the user does not specify initial phosphorus concentrations, SWAT will initialize levels of phosphorus in the different pools.

The concentration of solution phosphorus in all layers is initially set to 5 mg/kg soil. This concentration is representative of unmanaged land under native vegetation. A concentration of 25 mg/kg soil in the plow layer is considered representative of cropland (Cope et al., 1981).

The concentration of phosphorus in the active mineral pool is initialized to (Jones et al., 1984):

$$minP_{act,ly} = P_{solution,ly} \cdot \frac{1 - pai}{pai}$$ 11.1.1

where $minP_{act,ly}$ is the amount of phosphorus in the active mineral pool (mg/kg), $P_{solution,ly}$ is the amount of phosphorus in solution (mg/kg), and pai is the phosphorus availability index.

The concentration of phosphorus in the stable mineral pool is initialized to (Jones et al., 1984):

$$minP_{sta,ly} = 4 \cdot minP_{act,ly}$$ 11.1.2

where $minP_{sta,ly}$ is the amount of phosphorus in the stable mineral pool (mg/kg), and $minP_{act,ly}$ is the amount of phosphorus in the active mineral pool (mg/kg).

Organic phosphorus levels are assigned assuming that the N:P ratio for humic materials is 8:1. The concentration of humic organic phosphorus in a soil layer is calculated:

$$orgP_{hum,ly} = 0.125 \cdot orgN_{hum,ly}$$ 11.1.3

where $orgP_{hum,ly}$ is the concentration of humic organic phosphorus in the layer (mg/kg) and $orgN_{hum,ly}$ is the concentration of humic organic nitrogen in the layer (mg/kg).

Phosphorus in the fresh organic pool is set to zero in all layers except the top 10mm of soil. In the top 10 mm, the fresh organic phosphorus pool is set to 0.03% of the initial amount of residue on the soil surface.

$$orgP_{frsh,surf} = 0.0003 \cdot rsd_{surf}$$ 11.1.4

where $orgP_{frsh,surf}$ is the phosphorus in the fresh organic pool in the top 10mm (kg P/ha), and rsd_{surf} is material in the residue pool for the top 10mm of soil (kg/ha).

While SWAT allows nutrient levels to be input as concentrations, it performs all calculations on a mass basis. To convert a concentration to a mass, the concentration is multiplied by the bulk density and depth of the layer and divided by 100:

$$\frac{conc_P \cdot \rho_b \cdot depth_{ly}}{100} = \frac{\text{kg P}}{\text{ha}}$$ 11.1.5

where $conc_P$ is the concentration of phosphorus in a layer (mg/kg or ppm), ρ_b is the bulk density of the layer (Mg/m^3), and $depth_{ly}$ is the depth of the layer (mm).

Table 11-1: SWAT input variables that pertain to nitrogen pools.

Variable Name	Definition	Input File
SOL_SOLP	$P_{solution,ly}$: Initial soluble P concentration in soil layer (mg/kg or ppm)	.chm
SOL_ORGP	$orgP_{hum,ly}$: Initial humic organic phosphorus in soil layer (mg/kg or ppm)	.chm
PSP	pai: Phosphorus availability index	.bsn
RSDIN	rsd_{surf}: Material in the residue pool for the top 10mm of soil (kg ha^{-1})	.hru
SOL_BD	ρ_b: Bulk density of the layer (Mg/m^3)	.sol

11.2 MINERALIZATION & DECOMPOSITION / IMMOBILIZATION

Decomposition is the breakdown of fresh organic residue into simpler organic components. Mineralization is the microbial conversion of organic, plant-unavailable phosphorus to inorganic, plant-available phosphorus. Immobilization is the microbial conversion of plant-available inorganic soil phosphorus to plant-unavailable organic phosphorus.

The phosphorus mineralization algorithms in SWAT are **net** mineralization algorithms which incorporate immobilization into the equations. The phosphorus mineralization algorithms developed by Jones et al. (1984) are similar in structure to the nitrogen mineralization algorithms. Two sources are considered for mineralization: the fresh organic P pool associated with crop residue and microbial biomass and the active organic P pool associated with soil humus. Mineralization and decomposition are allowed to occur only if the temperature of the soil layer is above 0°C.

Mineralization and decomposition are dependent on water availability and temperature. Two factors are used in the mineralization and decomposition equations to account for the impact of temperature and water on these processes.

The nutrient cycling temperature factor is calculated:

$$\gamma_{tmp,ly} = 0.9 \cdot \frac{T_{soil,ly}}{T_{soil,ly} + \exp\left[9.93 - 0.312 \cdot T_{soil,ly}\right]} + 0.1 \qquad 11.2.1$$

where $\gamma_{tmp,ly}$ is the nutrient cycling temperature factor for layer ly, and $T_{soil,ly}$ is the temperature of layer ly (°C). The nutrient cycling temperature factor is never allowed to fall below 0.1.

The nutrient cycling water factor is calculated:

$$\gamma_{sw,ly} = \frac{SW_{ly}}{FC_{ly}} \qquad 11.2.2$$

where $\gamma_{sw,ly}$ is the nutrient cycling water factor for layer ly, SW_{ly} is the water content of layer ly on a given day (mm H_2O), and FC_{ly} is the water content of layer ly at field capacity (mm H_2O).). The nutrient cycling water factor is never allowed to fall below 0.05.

11.2.1 HUMUS MINERALIZATION

Phosphorus in the humus fraction is partitioned between the active and stable organic pools using the ratio of humus active organic N to stable organic N. The amount of phosphorus in the active and stable organic pools is calculated:

$$orgP_{act,ly} = orgP_{hum,ly} \cdot \frac{orgN_{act,ly}}{orgN_{act,ly} + orgN_{sta,ly}} \qquad 11.2.3$$

$$orgP_{sta,ly} = orgP_{hum,ly} \cdot \frac{orgN_{sta,ly}}{orgN_{act,ly} + orgN_{sta,ly}} \qquad 11.2.4$$

where $orgP_{act,ly}$ is the amount of phosphorus in the active organic pool (kg P/ha), $orgP_{sta,ly}$ is the amount of phosphorus in the stable organic pool (kg P/ha), $orgP_{hum,ly}$ is the concentration of humic organic phosphorus in the layer (kg P/ha), $orgN_{act,ly}$ is the amount of nitrogen in the active organic pool (kg N/ha), and $orgN_{sta,ly}$ is the amount of nitrogen in the stable organic pool (kg N/ha).

Mineralization from the humus active organic P pool is calculated:

$$P_{mina,ly} = 1.4 \cdot \beta_{min} \cdot \left(\gamma_{tmp,ly} \cdot \gamma_{sw,ly}\right)^{1/2} \cdot orgP_{act,ly} \qquad 11.2.5$$

where $P_{mina,ly}$ is the phosphorus mineralized from the humus active organic P pool (kg P/ha), β_{min} is the rate coefficient for mineralization of the humus active organic nutrients, $\gamma_{tmp,ly}$ is the nutrient cycling temperature factor for layer ly, $\gamma_{sw,ly}$

is the nutrient cycling water factor for layer ly, and $orgP_{act,ly}$ is the amount of phosphorus in the active organic pool (kg P/ha).

Phosphorus mineralized from the humus active organic pool is added to the solution P pool in the layer.

11.2.2 RESIDUE DECOMPOSITION & MINERALIZATION

Decomposition and mineralization of the fresh organic phosphorus pool is allowed only in the first soil layer. Decomposition and mineralization are controlled by a decay rate constant that is updated daily. The decay rate constant is calculated as a function of the C:N ratio and C:P ratio of the residue, temperature and soil water content.

The C:N ratio of the residue is calculated:

$$\varepsilon_{C:N} = \frac{0.58 \cdot rsd_{ly}}{orgN_{frsh,ly} + NO3_{ly}}$$ 11.2.6

where $\varepsilon_{C:N}$ is the C:N ratio of the residue in the soil layer, rsd_{ly} is the residue in layer ly (kg/ha), 0.58 is the fraction of residue that is carbon, $orgN_{frsh,ly}$ is the nitrogen in the fresh organic pool in layer ly (kg N/ha), and $NO3_{ly}$ is the amount of nitrate in layer ly (kg N/ha).

The C:P ratio of the residue is calculated:

$$\varepsilon_{C:P} = \frac{0.58 \cdot rsd_{ly}}{orgP_{frsh,ly} + P_{solution,ly}}$$ 11.2.7

where $\varepsilon_{C:P}$ is the C:P ratio of the residue in the soil layer, rsd_{ly} is the residue in layer ly (kg/ha), 0.58 is the fraction of residue that is carbon, $orgP_{frsh,ly}$ is the phosphorus in the fresh organic pool in layer ly (kg P/ha), and $P_{solution,ly}$ is the amount of phosphorus in solution in layer ly (kg P/ha).

The decay rate constant defines the fraction of residue that is decomposed. The decay rate constant is calculated:

$$\delta_{ntr,ly} = \beta_{rsd} \cdot \gamma_{ntr,ly} \cdot \left(\gamma_{tmp,ly} \cdot \gamma_{sw,ly}\right)^{1/2}$$ 11.2.8

where $\delta_{ntr,ly}$ is the residue decay rate constant, β_{rsd} is the rate coefficient for mineralization of the residue fresh organic nutrients, $\gamma_{ntr,ly}$ is the nutrient cycling

residue composition factor for layer *ly*, $\gamma_{tmp,ly}$ is the nutrient cycling temperature factor for layer *ly*, and $\gamma_{sw,ly}$ is the nutrient cycling water factor for layer *ly*.

The nutrient cycling residue composition factor is calculated:

$$\gamma_{ntr,ly} = \min \begin{cases} \exp\left[-0.693 \cdot \frac{(\varepsilon_{C:N} - 25)}{25}\right] \\ \exp\left[-0.693 \cdot \frac{(\varepsilon_{C:P} - 200)}{200}\right] \\ 1.0 \end{cases}$$ 11.2.9

where $\gamma_{ntr,ly}$ is the nutrient cycling residue composition factor for layer *ly*, $\varepsilon_{C:N}$ is the C:N ratio on the residue in the soil layer, and $\varepsilon_{C:P}$ is the C:P ratio on the residue in the soil layer.

Mineralization from the residue fresh organic P pool is then calculated:

$$P_{minf,ly} = 0.8 \cdot \delta_{ntr,ly} \cdot orgP_{frsh,ly}$$ 11.2.10

where $P_{minf,ly}$ is the phosphorus mineralized from the fresh organic P pool (kg P/ha), $\delta_{ntr,ly}$ is the residue decay rate constant, and $orgP_{frsh,ly}$ is the phosphorus in the fresh organic pool in layer *ly* (kg P/ha). Phosphorus mineralized from the fresh organic pool is added to the solution P pool in the layer.

Decomposition from the residue fresh organic P pool is calculated:

$$P_{dec,ly} = 0.2 \cdot \delta_{ntr,ly} \cdot orgP_{frsh,ly}$$ 11.2.11

where $P_{dec,ly}$ is the phosphorus decomposed from the fresh organic P pool (kg P/ha), $\delta_{ntr,ly}$ is the residue decay rate constant, and $orgP_{frsh,ly}$ is the phosphorus in the fresh organic pool in layer *ly* (kg P/ha). Phosphorus decomposed from the fresh organic pool is added to the humus organic pool in the layer.

Table 11-2: SWAT input variables that pertain to mineralization.

Variable Name	Definition	Input File
CMN	β_{min}: Rate coefficient for mineralization of the humus active organic nutrients	.bsn
RSDCO	β_{rsd}: Rate coefficient for mineralization of the residue fresh organic nutrients	.bsn
RSDCO_PL	β_{rsd}: Rate coefficient for mineralization of the residue fresh organic nutrients	crop.dat

11.3 SORPTION OF INORGANIC P

Many studies have shown that after an application of soluble P fertilizer, solution P concentration decreases rapidly with time due to reaction with the soil. This initial "fast" reaction is followed by a much slower decrease in solution P that may continue for several years (Barrow and Shaw, 1975; Munns and Fox, 1976; Rajan and Fox, 1972; Sharpley, 1982). In order to account for the initial rapid decrease in solution P, SWAT assumes a rapid equilibrium exists between solution P and an "active" mineral pool. The subsequent slow reaction is simulated by the slow equilibrium assumed to exist between the "active" and "stable" mineral pools. The algorithms governing movement of inorganic phosphorus between these three pools are taken from Jones et al. (1984).

Equilibration between the solution and active mineral pool is governed by the phosphorus availability index. This index specifies the fraction of fertilizer P which is in solution after an incubation period, i.e. after the rapid reaction period.

A number of methods have been developed to measure the phosphorus availability index. Jones et al. (1984) recommends a method outlined by Sharpley et al. (1984) in which various amounts of phosphorus are added in solution to the soil as K_2HPO_4. The soil is wetted to field capacity and then dried slowly at 25°C. When dry, the soil is rewetted with deionized water. The soil is exposed to several wetting and drying cycles over a 6-month incubation period. At the end of the incubation period, solution phosphorus is determined by extraction with anion exchange resin.

The P availability index is then calculated:

$$pai = \frac{P_{solution,f} - P_{solution,i}}{fert_{minP}}$$ 11.3.1

where pai is the phosphorus availability index, $P_{solution,f}$ is the amount of phosphorus in solution after fertilization and incubation, $P_{solution,i}$ is the amount of phosphorus in solution before fertilization, and $fert_{minP}$ is the amount of soluble P fertilizer added to the sample.

The movement of phosphorus between the solution and active mineral pools is governed by the equilibration equations:

$$P_{sol|act,ly} = P_{solution,ly} - minP_{act,ly} \cdot \left(\frac{pai}{1-pai} \right)$$

$$\text{if } P_{solution,ly} > minP_{act,ly} \cdot \left(\frac{pai}{1-pai} \right) \qquad 11.3.2$$

$$P_{sol|act,ly} = 0.1 \cdot \left[P_{solution,ly} - minP_{act,ly} \cdot \left(\frac{pai}{1-pai} \right) \right]$$

$$\text{if } P_{solution,ly} < minP_{act,ly} \cdot \left(\frac{pai}{1-pai} \right) \qquad 11.3.3$$

where $P_{sol|act,ly}$ is the amount of phosphorus transferred between the soluble and active mineral pool (kg P/ha), $P_{solution,ly}$ is the amount of phosphorus in solution (kg P/ha), $minP_{act,ly}$ is the amount of phosphorus in the active mineral pool (kg P/ha), and *pai* is the phosphorus availability index. When $P_{sol|act,ly}$ is positive, phosphorus is being transferred from solution to the active mineral pool. When $P_{sol|act,ly}$ is negative, phosphorus is being transferred from the active mineral pool to solution. Note that the rate of flow from the active mineral pool to solution is $1/10^{th}$ the rate of flow from solution to the active mineral pool.

SWAT simulates slow phosphorus sorption by assuming the active mineral phosphorus pool is in slow equilibrium with the stable mineral phosphorus pool. At equilibrium, the stable mineral pool is 4 times the size of the active mineral pool.

When not in equilibrium, the movement of phosphorus between the active and stable mineral pools is governed by the equations:

$$P_{act|sta,ly} = \beta_{eqP} \cdot \left(4 \cdot minP_{act,ly} - minP_{sta,ly} \right)$$

$$\text{if } minP_{sta,ly} < 4 \cdot minP_{act,ly} \qquad 11.3.4$$

$$P_{act|sta,ly} = 0.1 \cdot \beta_{eqP} \cdot \left(4 \cdot minP_{act,ly} - minP_{sta,ly} \right)$$

$$\text{if } minP_{sta,ly} > 4 \cdot minP_{act,ly} \qquad 11.3.5$$

where $P_{act|sta,ly}$ is the amount of phosphorus transferred between the active and stable mineral pools (kg P/ha), β_{eqP} is the slow equilibration rate constant (0.0006 d^{-1}), $minP_{act,ly}$ is the amount of phosphorus in the active mineral pool (kg P/ha), and $minP_{sta,ly}$ is the amount of phosphorus in the stable mineral pool (kg P/ha). When $P_{act|sta,ly}$ is positive, phosphorus is being transferred from the active mineral pool to the stable mineral pool. When $P_{act|sta,ly}$ is negative, phosphorus is being transferred from the stable mineral pool to the active mineral pool. Note that the rate of flow from the stable mineral pool to the active mineral pool is 1/10th the rate of flow from the active mineral pool to the stable mineral pool.

Table 11-3: SWAT input variables that pertain to inorganic P sorption processes.

Variable Name	Definition	Input File
PSP	*pai*: Phosphorus availability index	.bsn

11.4 LEACHING

The primary mechanism of phosphorus movement in the soil is by diffusion. Diffusion is the migration of ions over small distances (1-2 mm) in the soil solution in response to a concentration gradient. The concentration gradient is created when plant roots remove soluble phosphorus from soil solution, depleting solution P in the root zone.

Due to the low mobility of phosphorus, SWAT allows soluble P to leach only from the top 10 mm of soil into the first soil layer. The amount of solution P moving from the top 10 mm into the first soil layer is:

$$P_{perc} = \frac{P_{solution,surf} \cdot w_{perc,surf}}{10 \cdot \rho_b \cdot depth_{surf} \cdot k_{d,perc}} \qquad 11.4.1$$

where P_{perc} is the amount of phosphorus moving from the top 10 mm into the first soil layer (kg P/ha), $P_{solution,surf}$ is the amount of phosphorus in solution in the top 10 mm (kg P/ha), $w_{perc,surf}$ is the amount of water percolating to the first soil layer from the top 10 mm on a given day (mm H$_2$O), ρ_b is the bulk density of the top 10 mm (Mg/m^3) (assumed to be equivalent to bulk density of first soil layer),

$depth_{surf}$ is the depth of the "surface" layer (10 mm), and $k_{d,perc}$ is the phosphorus percolation coefficient (10 m³/Mg). The phosphorus percolation coefficient is the ratio of the phosphorus concentration in the surface 10 mm of soil to the concentration of phosphorus in percolate.

Table 11-4: SWAT input variables that pertain to phosphorus leaching.

Variable Name	Definition	Input File
SOL_BD	ρ_b: Bulk density of the layer (Mg/m³)	.sol
PPERCO	$k_{d,perc}$: Phosphorus percolation coefficient (10 m³/Mg)	.bsn

11.5 NOMENCLATURE

FC_{ly} Water content of layer ly at field capacity (mm H_2O)

$NO3_{ly}$ Nitrate content of soil layer ly (kg NO_3-N/ha)

$P_{act|sta,ly}$ Amount of phosphorus transferred between the active and stable mineral pools (kg P/ha)

$P_{dec,ly}$ Phosphorus decomposed from the fresh organic P pool (kg P/ha)

$P_{mina,ly}$ Phosphorus mineralized from the humus active organic P pool (kg P/ha)

$P_{minf,ly}$ Phosphorus mineralized from the fresh organic P pool (kg P/ha),

P_{perc} Amount of phosphorus moving from the top 10 mm into the first soil layer (kg P/ha)

$P_{solution,ly}$ Amount of phosphorus in solution (mg/kg)

$P_{sol|act,ly}$ Amount of phosphorus transferred between the soluble and active mineral pool (kg P/ha)

SW_{ly} Soil water content of layer ly (mm H_2O)

$T_{soil,ly}$ Temperature of layer ly (°C)

$conc_P$ Concentration of phosphorus in a layer (mg/kg or ppm)

$depth_{ly}$ Depth of the layer (mm)

$k_{d,perc}$ Phosphorus percolation coefficient (10 m³/Mg)

$minP_{act,ly}$ Amount of phosphorus in the active mineral pool (mg/kg or kg P/ha)

$minP_{sta,ly}$ Amount of phosphorus in the stable mineral pool (mg/kg or kg P/ha)

$orgN_{act,ly}$ Nitrogen in the active organic pool in layer ly (mg/kg or kg N/ha)

$orgN_{frsh,ly}$ Nitrogen in the fresh organic pool in layer ly (kg N/ha)

$orgN_{hum,ly}$ Amount of nitrogen in humic organic pool in the layer (mg/kg or kg N/ha)

$orgN_{sta,ly}$ Nitrogen in the stable organic pool in layer ly (mg/kg or kg N/ha)

$orgP_{act,ly}$ Amount of phosphorus in the active organic pool (kg P/ha)

$orgP_{frsh,ly}$ Phosphorus in the fresh organic pool in layer ly (kg P/ha)

$orgP_{hum,ly}$ Amount of phosphorus in humic organic pool in the layer (mg/kg or kg P/ha)

$orgP_{sta,ly}$ Amount of phosphorus in the stable organic pool (kg P/ha)

pai Phosphorus availability index

rsd_{ly} Residue in layer ly (kg/ha)

$w_{perc,ly}$ Amount of water percolating to the underlying soil layer on a given day (mm H_2O)

β_{eqP} Slow equilibration rate constant (0.0006 d^{-1})
β_{min} Rate coefficient for mineralization of the humus active organic nutrients
β_{rsd} Rate coefficient for mineralization of the residue fresh organic nutrients
$\delta_{ntr,ly}$ Residue decay rate constant
$\varepsilon_{C:N}$ Residue C:N ratio in the soil layer
$\varepsilon_{C:P}$ Residue C:P ratio in the soil layer
$\gamma_{ntr,ly}$ Nutrient cycling residue composition factor for layer ly
$\gamma_{sw,ly}$ Nutrient cycling water factor for layer ly
$\gamma_{tmp,ly}$ Nutrient cycling temperature factor for layer ly
ρ_b Bulk density of the layer (Mg/m^3)

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CHAPTER 12

EQUATIONS: PESTICIDES

One of the primary purposes of tillage and harvesting practices in early farming systems was to remove as much plant residue from the field as possible so that pests had no food source to sustain them until the next growing season. As research linked erosion to lack of soil cover, farmers began to perform fewer tillage operations and altered harvesting methods to leave more residue. As mechanical methods of pest control were minimized or eliminated, chemical methods of pest control began to assume a key role in the management of unwanted organisms.

Pesticides are toxic by design, and there is a natural concern about the impact of their presence in the environment on human health and environmental quality. The fate and transport of a pesticide are governed by properties such as solubility in water, volatility and ease of degradation. The algorithms in SWAT used to model pesticide movement and fate are adapted from GLEAMS (Leonard et al., 1987).

Pesticide may be aerially applied to an HRU with some fraction intercepted by plant foliage and some fraction reaching the soil. Pesticide may also be incorporated into the soil through tillage. SWAT monitors pesticide amounts on foliage and in all soil layers. Figure 12-1 shows the potential pathways and processes simulated in SWAT.
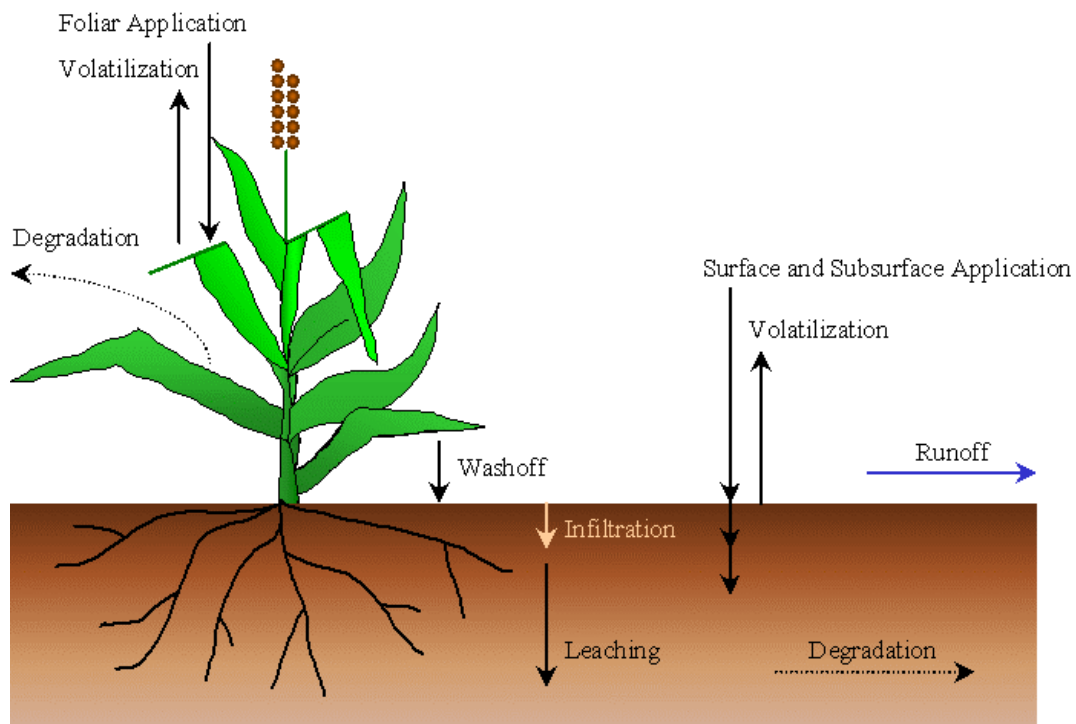
Figure 12-1: Pesticide fate and transport in SWAT.

12.1 WASH-OFF

A portion of the pesticide on plant foliage may be washed off during rain events. The fraction washed off is a function of plant morphology, pesticide solubility, and the timing and intensity of the rainfall event. Wash-off will occur when the amount of precipitation on a given day exceeds 2.54 mm.

The amount of pesticide washing off plant foliage during a precipitation event on a given day is calculated:

$$pst_{f,wsh} = fr_{wsh} \cdot pst_f \qquad\qquad 12.1.1$$

where $pst_{f,wsh}$ is the amount of pesticide on foliage that is washed off the plant and onto the soil surface on a given day (kg pst/ha), fr_{wsh} is the wash-off fraction for the pesticide, and pst_f is the amount of pesticide on the foliage (kg pst/ha). The wash-off fraction represents the portion of the pesticide on the foliage that is dislodgable.

Table 12-1: SWAT input variables that pertain to pesticide wash-off.

Variable Name	Definition	Input File
WOF	fr_{wsh}: Wash-off fraction for the pesticide	pest.dat

12.2 DEGRADATION

Degradation is the conversion of a compound into less complex forms. A compound in the soil may degrade upon exposure to light (photo degradation), reaction with chemicals present in the soil (chemical degradation) or through use as a substrate for organisms (biodegradation).

The majority of pesticides in use today are organic compounds. Because organic compounds contain carbon, which is used by microbes in biological reactions to produce energy, organic pesticides may be susceptible to microbial degradation. In contrast, pesticides that are inorganic are not susceptible to microbial degradation. Examples of pesticides that will not degrade are lead arsenate, a metallic salt commonly applied in orchards before DDT was invented, and arsenic acid, a compound formerly used to defoliate cotton.

Pesticides vary in their susceptibility to degradation. Compounds with chain structures are easier to break apart than compounds containing aromatic rings or other complex structures. The susceptibility of a pesticide to degradation is quantified by the pesticide's half-life.

The half-life for a pesticide defines the number of days required for a given pesticide concentration to be reduced by one-half. The soil half-life entered for a pesticide is a lumped parameter that includes the net effect of volatilization, photolysis, hydrolysis, biological degradation and chemical reactions in the soil. Because pesticide on foliage degrades more rapidly than pesticide in the soil, SWAT allows a different half-life to be defined for foliar degradation.

Pesticide degradation or removal in all soil layers is governed by first-order kinetics:

$$pst_{s,ly,t} = pst_{s,ly,o} \cdot \exp[-k_{p,soil} \cdot t] \qquad 12.2.1$$

where $pst_{s,ly,t}$ is the amount of pesticide in the soil layer at time t (kg pst/ha), $pst_{s,ly,o}$ is the initial amount of pesticide in the soil layer (kg pst/ha), $k_{p,soil}$ is the rate constant for degradation or removal of the pesticide in soil (1/day), and t is the time elapsed since the initial pesticide amount was determined (days). The rate constant is related to the soil half-life as follows:

$$t_{1/2,s} = \frac{0.693}{k_{p,soil}} \qquad 12.2.2$$

where $t_{1/2,s}$ is the half-life of the pesticide in the soil (days).

The equation governing pesticide degradation on foliage is:

$$pst_{f,t} = pst_{f,o} \cdot \exp[-k_{p,foliar} \cdot t] \qquad 12.2.3$$

where $pst_{f,t}$ is the amount of pesticide on the foliage at time t (kg pst/ha), $pst_{f,o}$ is the initial amount of pesticide on the foliage (kg pst/ha), $k_{p,foliar}$ is the rate constant for degradation or removal of the pesticide on foliage (1/day), and t is the time elapsed since the initial pesticide amount was determined (days). The rate constant is related to the foliar half-life as follows:

$$t_{1/2,f} = \frac{0.693}{k_{p,foliar}} \qquad 12.2.4$$

where $t_{1/2,f}$ is the half-life of the pesticide on foliage (days).

Table 12-2: SWAT input variables that pertain to pesticide degradation.

Variable Name	Definition	Input File
HLIFE_S	$t_{1/2,s}$: Half-life of the pesticide in the soil (days)	pest.dat
HLIFE_F	$t_{1/2,f}$: Half-life of the pesticide on foliage (days)	pest.dat

12.3 LEACHING

Highly water-soluble pesticides can be transported with percolation deep into the soil profile and potentially pollute shallow groundwater systems. The algorithms used by SWAT to calculated pesticide leaching simultaneously solve for loss of pesticide in surface runoff and lateral flow also. These algorithms are reviewed in Chapter 15.

12.4 NOMENCLATURE

fr_{wsh} Wash-off fraction for the pesticide
$k_{p,foliar}$ Rate constant for degradation or removal of the pesticide on foliage (1/day)
$k_{p,soil}$ Rate constant for degradation or removal of the pesticide in soil (1/day)
pst_f Amount of pesticide on the foliage (kg pst/ha)
$pst_{f,wsh}$ Amount of pesticide on foliage that is washed off the plant and onto the soil surface on a given day (kg pst/ha)
$pst_{s,ly}$ Amount of pesticide in the soil (kg pst/ha)
t Time elapsed since the initial pesticide amount was determined (days)
$t_{1/2,f}$ Half-life of the pesticide on foliage (days)
$t_{1/2,s}$ Half-life of the pesticide in the soil (days)

12.5 REFERENCES

Leonard, R.A., W.G. Knisel., and D.A. Still. 1987. GLEAMS: Groundwater loading effects of agricultural management systems. Trans. ASAE. 30:1403-1418.

EROSION

Transport of sediment, nutrients and pesticides from land areas to water bodies is a consequence of weathering that acts on landforms. Soil and water conservation planning requires knowledge of the relations between factors that cause loss of soil and water and those that help to reduce such losses.

The following three chapters review the methodology used by SWAT to simulate erosion processes.
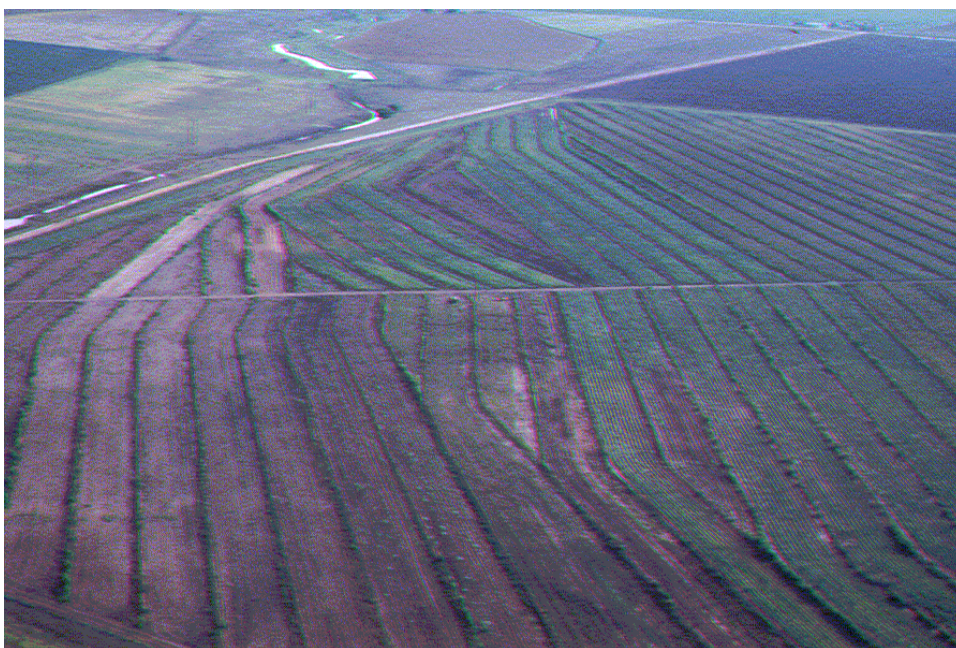
CHAPTER 13

EQUATIONS: SEDIMENT

Erosion caused by rainfall and runoff is computed with the Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975). MUSLE is a modified version of the Universal Soil Loss Equation (USLE) developed by Wischmeier and Smith (1965, 1978).

USLE predicts average annual gross erosion as a function of rainfall energy. In MUSLE, the rainfall energy factor is replaced with a runoff factor. This improves the sediment yield prediction, eliminates the need for delivery ratios, and allows the equation to be applied to individual storm events. Sediment yield

prediction is improved because runoff is a function of antecedent moisture condition as well as rainfall energy. Delivery ratios (the sediment yield at any point along the channel divided by the source erosion above that point) are required by the USLE because the rainfall factor represents energy used in detachment only. Delivery ratios are not needed with MUSLE because the runoff factor represents energy used in detaching and transporting sediment.

13.1 MUSLE

The modified universal soil loss equation (Williams, 1995) is:

$$sed = 11.8 \cdot \left(Q_{surf} \cdot q_{peak} \cdot area_{hru}\right)^{0.56} \cdot K_{USLE} \cdot C_{USLE} \cdot P_{USLE} \cdot LS_{USLE} \cdot CFRG \quad 13.1.1$$

where sed is the sediment yield on a given day (metric tons), Q_{surf} is the surface runoff volume (mm H_2O/ha), q_{peak} is the peak runoff rate (m^3/s), $area_{hru}$ is the area of the HRU (ha), K_{USLE} is the USLE soil erodibility factor (0.013 metric ton m^2 hr/(m^3-metric ton cm)), C_{USLE} is the USLE cover and management factor, P_{USLE} is the USLE support practice factor, LS_{USLE} is the USLE topographic factor and $CFRG$ is the coarse fragment factor. Surface runoff and peak rate calculations are reviewed in Chapter 6. The USLE factors are discussed in the following sections.

13.1.1 SOIL ERODIBILITY FACTOR

Some soils erode more easily than others even when all other factors are the same. This difference is termed soil erodibility and is caused by the properties of the soil itself. Wischmeier and Smith (1978) define the soil erodibility factor as the soil loss rate per erosion index unit for a specified soil as measured on a unit plot. A unit plot is 22.1-m (72.6-ft) long, with a uniform length-wise slope of 9-percent, in continuous fallow, tilled up and down the slope. Continuous fallow is defined as land that has been tilled and kept free of vegetation for more than 2 years. The units for the USLE soil erodibility factor in MUSLE are numerically equivalent to the traditional English units of 0.01 (ton acre hr)/(acre ft-ton inch).

Wischmeier and Smith (1978) noted that a soil type usually becomes less erodible with decrease in silt fraction, regardless of whether the corresponding increase is in the sand fraction or clay fraction.

Direct measurement of the erodibility factor is time consuming and costly. Wischmeier et al. (1971) developed a general equation to calculate the soil erodibility factor when the silt and very fine sand content makes up less than 70% of the soil particle size distribution.

$$K_{USLE} = \frac{0.00021 \cdot M^{1.14} \cdot (12 - OM) + 3.25 \cdot (c_{soilstr} - 2) + 2.5 \cdot (c_{perm} - 3)}{100} \qquad 13.1.2$$

where K_{USLE} is the soil erodibility factor, M is the particle-size parameter, OM is the percent organic matter (%), $c_{soilstr}$ is the soil structure code used in soil classification, and c_{perm} is the profile permeability class.

The particle-size parameter, M, is calculated

$$M = (m_{silt} + m_{vfs}) \cdot (100 - m_c) \qquad 13.1.3$$

where m_{silt} is the percent silt content (0.002-0.05 mm diameter particles), m_{vfs} is the percent very fine sand content (0.05-0.10 mm diameter particles), and m_c is the percent clay content (< 0.002 mm diameter particles).

The percent organic matter content, OM, of a layer can be calculated:

$$OM = 1.72 \cdot orgC \qquad 13.1.4$$

where $orgC$ is the percent organic carbon content of the layer (%).

Soil structure refers to the aggregation of primary soil particles into compound particles which are separated from adjoining aggregates by surfaces of weakness. An individual natural soil aggregate is called a ped. Field description of soil structure notes the shape and arrangement of peds, the size of peds, and the distinctness and durability of visible peds. USDA Soil Survey terminology for structure consists of separate sets of terms defining each of these three qualities. Shape and arrangement of peds are designated as type of soil structure; size of peds as class; and degree of distinctness as grade.

The soil-structure codes for equation 13.1.2 are defined by the type and class of soil structure present in the layer. There are four primary types of structure:

-Platy, with particles arranged around a plane, generally horizontal

-Prismlike, with particles arranged around a verticle line and bounded by relatively flat vertical surfaces

-Blocklike or polyhedral, with particles arranged around a point and bounded by flat or rounded surfaces which are casts of the molds formed by the faces of surrounding peds

-Spheroidal or polyhedral, with particles arranged around a point and bounded by curved or very irregular surfaces that are not accomodated to the adjoining aggregates

Each of the last three types has two subtypes:

-Prismlike
   Prismatic: without rounded upper ends
   Columnar: with rounded caps

-Blocklike
   Angular Blocky: bounded by planes intersecting at relatively sharp angles
   Subangular Blocky: having mixed rounded and plane faces with vertices mostly rounded

-Spheroidal
   Granular: relatively non-porous
   Crumb: very porous

The size criteria for the class will vary by type of structure and are summarized in Table 13-1. The codes assigned to $c_{soilstr}$ are:

   1   very fine granular
   2   fine granular
   3   medium or coarse granular
   4   blocky, platy, prismlike or massive

Table 13-1: Size classes of soil structure

Size Classes	Platy	Prismatic and Columnar	Blocky	Granular
Very fine	< 1 mm	< 10 mm	< 5 mm	< 1 mm
Fine	1-2 mm	10-20 mm	5-10 mm	1-2 mm
Medium	2-5 mm	20-50 mm	10-20 mm	2-5 mm
Coarse	5-10 mm	50-100 mm	20-50 mm	5-10 mm
Very coarse	> 10 mm	> 100 mm	> 50 mm	> 10 mm

Permeability is defined as the capacity of the soil to transmit water and air through the most restricted horizon (layer) when moist. The profile permeability classes are based on the lowest saturated hydraulic conductivity in the profile. The codes assigned to c_{perm} are:

1   rapid (> 150 mm/hr)
2   moderate to rapid (50-150 mm/hr)
3   moderate (15-50 mm/hr)
4   slow to moderate (5-15 mm/hr)
5   slow (1-5 mm/hr)
6   very slow (< 1 mm/hr)

Williams (1995) proposed an alternative equation:

$$K_{USLE} = f_{csand} \cdot f_{cl-si} \cdot f_{orgc} \cdot f_{hisand}$$ 13.1.5

where f_{csand} is a factor that gives low soil erodibility factors for soils with high coarse-sand contents and high values for soils with little sand, f_{cl-si} is a factor that gives low soil erodibility factors for soils with high clay to silt ratios, f_{orgc} is a factor that reduces soil erodibility for soils with high organic carbon content, and f_{hisand} is a factor that reduces soil erodibility for soils with extremely high sand contents. The factors are calculated:

$$f_{csand} = \left(0.2 + 0.3 \cdot \exp\left[-0.256 \cdot m_s \cdot \left(1 - \frac{m_{silt}}{100} \right) \right] \right)$$ 13.1.6

$$f_{cl-si} = \left(\frac{m_{silt}}{m_c + m_{silt}} \right)^{0.3}$$ 13.1.7

$$f_{orgc} = \left(1 - \frac{0.25 \cdot orgC}{orgC + \exp[3.72 - 2.95 \cdot orgC]} \right)$$ 13.1.8

$$f_{hisand} = \left(1 - \frac{0.7 \cdot \left(1 - \frac{m_s}{100} \right)}{\left(1 - \frac{m_s}{100} \right) + \exp\left[-5.51 + 22.9 \cdot \left(1 - \frac{m_s}{100} \right) \right]} \right)$$ 13.1.9

where m_s is the percent sand content (0.05-2.00 mm diameter particles), m_{silt} is the percent silt content (0.002-0.05 mm diameter particles), m_c is the percent clay content (< 0.002 mm diameter particles), and $orgC$ is the percent organic carbon content of the layer (%).

13.1.2 COVER AND MANAGEMENT FACTOR

The USLE cover and management factor, C_{USLE}, is defined as the ratio of soil loss from land cropped under specified conditions to the corresponding loss

from clean-tilled, continuous fallow (Wischmeier and Smith, 1978). The plant canopy affects erosion by reducing the effective rainfall energy of intercepted raindrops. Water drops falling from the canopy may regain appreciable velocity but it will be less than the terminal velocity of free-falling raindrops. The average fall height of drops from the canopy and the density of the canopy will determine the reduction in rainfall energy expended at the soil surface. A given percentage of residue on the soil surface is more effective that the same percentage of canopy cover. Residue intercepts falling raindrops so near the surface that drops regain no fall velocity. Residue also obstructs runoff flow, reducing its velocity and transport capacity.

Because plant cover varies during the growth cycle of the plant, SWAT updates C_{USLE} daily using the equation:

$$C_{USLE} = \exp\left(\left[\ln(0.8) - \ln\left(C_{USLE,mn}\right)\right] \cdot \exp\left[-0.00115 \cdot rsd_{surf}\right] + \ln\left[C_{USLE,mn}\right]\right) \quad 13.1.10$$

where $C_{USLE,mn}$ is the minimum value for the cover and management factor for the land cover, and rsd_{surf} is the amount of residue on the soil surface (kg/ha).

The minimum C factor can be estimated from a known average annual C factor using the following equation (Arnold and Williams, 1995):

$$C_{USLE,mn} = 1.463 \ln\left[C_{USLE,aa}\right] + 0.1034 \quad\quad\quad 13.1.11$$

where $C_{USLE,mn}$ is the minimum C factor for the land cover and $C_{USLE,aa}$ is the average annual C factor for the land cover.

13.1.3 SUPPORT PRACTICE FACTOR

The support practice factor, P_{USLE}, is defined as the ratio of soil loss with a specific support practice to the corresponding loss with up-and-down slope culture. Support practices include contour tillage, stripcropping on the contour, and terrace systems. Stabilized waterways for the disposal of excess rainfall are a necessary part of each of these practices.

Contour tillage and planting provides almost complete protection against erosion from storms of low to moderate intensity, but little or no protection against occasional severe storms that cause extensive breakovers of contoured

rows. Contouring is most effective on slopes of 3 to 8 percent. Values for P_{USLE} and slope-length limits for contour support practices are given in Table 13-2.

Table 13-2: P factor values and slope-length limits for contouring (Wischmeier and Smith, 1978).

Land slope (%)	P_{USLE}	Maximum length (m)
1 to 2	0.60	122
3 to 5	0.50	91
6 to 8	0.50	61
9 to 12	0.60	37
13 to 16	0.70	24
17 to 20	0.80	18
21 to 25	0.90	15

Stripcropping is a practice in which contoured strips of sod are alternated with equal-width strips of row crop or small grain. Recommended values for contour stripcropping are given in Table 13-3.

Table 13-3: P factor values, maximum strip width and slope-length limits for contour stripcropping (Wischmeier and Smith, 1978).

Land slope	P_{USLE} values[1]			Strip width	Maximum
(%)	A	B	C	(m)	length (m)
1 to 2	0.30	0.45	0.60	40	244
3 to 5	0.25	0.38	0.50	30	183
6 to 8	0.25	0.38	0.50	30	122
9 to 12	0.30	0.45	0.60	24	73
13 to 16	0.35	0.52	0.70	24	49
17 to 20	0.40	0.60	0.80	18	37
21 to 25	0.45	0.68	0.90	15	30

[1]P values:

A: For 4-year rotation of row crop, small grain with meadow seeding, and 2 years of meadow. A second row crop can replace the small grain if meadow is established in it.
B: For 4-year rotation of 2 years row crop, winter grain with meadow seeding, and 1-year meadow.
C: For alternate strips of row crop and winter grain

Terraces are a series of horizontal ridges made in a hillside. There are several types of terraces. Broadbase terraces are constructed on gently sloping land and the channel and ridge are cropped the same as the interterrace area. The steep backslope terrace, where the backslope is in sod, is most common on steeper land. Impoundment terraces are terraces with underground outlets.

Terraces divide the slope of the hill into segments equal to the horizontal terrace interval. With terracing, the slope length is the terrace interval. For broadbase terraces, the horizontal terrace interval is the distance from the center of the ridge to the center of the channel for the terrace below. The horizontal terrace interval for steep backslope terraces is the distance from the point where

cultivation begins at the base of the ridge to the base of the frontslope of the terrace below.

Values for P_{USLE} for contour farming terraced fields are listed in Table 13-4. These values apply to broadbase, steep backslope and level terraces. Keep in mind that the values given in Table 13-4 do not account for all erosion control benefits of terraces. The shorter slope-length used in the calculation of the length-slope factor will produce additional reduction.

Table 13-4: P factor values for contour-farmed terraced fields[1]

Land slope (%)	Farm planning		Computing sediment yield[3]	
	Contour P factor[2]	Stripcrop P factor	Graded channels sod outlets	Steep backslope underground outlets
1 to 2	0.60	0.30	0.12	0.05
3 to 8	0.50	0.25	0.10	0.05
9 to 12	0.60	0.30	0.12	0.05
13 to 16	0.70	0.35	0.14	0.05
17 to 20	0.80	0.40	0.16	0.06
21 to 25	0.90	0.45	0.18	0.06

[1]Slope length is the horizontal terrace interval. The listed values are for contour farming. No additional contouring factor is used in the computation.
[2] Use these values for control of interterrace erosion within specified soil loss tolerances.
[3] These values include entrapment efficiency and are used for control of offsite sediment within limits and for estimating the field's contribution to watershed sediment yield.

13.1.4 TOPOGRAPHIC FACTOR

The topographic factor, LS_{USLE}, is the expected ratio of soil loss per unit area from a field slope to that from a 22.1-m length of uniform 9 percent slope under otherwise identical conditions. The topographic factor is calculated:

$$LS_{USLE} = \left(\frac{L_{hill}}{22.1} \right)^m \cdot \left(65.41 \cdot \sin^2(\alpha_{hill}) + 4.56 \cdot \sin \alpha_{hill} + 0.065 \right) \qquad 13.1.12$$

where L_{hill} is the slope length (m), m is the exponential term, and α_{hill} is the angle of the slope. The exponential term, m, is calculated:

$$m = 0.6 \cdot (1 - \exp[-35.835 \cdot slp]) \qquad 13.1.13$$

where slp is the slope of the HRU expressed as rise over run (m/m). The relationship between α_{hill} and slp is:

$$slp = \tan \alpha_{hill} \qquad 13.1.14$$

13.1.5 COARSE FRAGMENT FACTOR

The coarse fragment factor is calculated:

$$CFRG = \exp(-0.053 \cdot rock) \qquad\qquad 13.1.15$$

where *rock* is the percent rock in the first soil layer (%).

Table 13-5: SWAT input variables that pertain to sediment yield.

Variable Name	Definition	Input File
USLE_K	K_{USLE}: USLE soil erodibility factor (0.013 metric ton m^2 hr/(m^3-metric ton cm))	.sol
USLE_C	$C_{USLE,mn}$: Minimum value for the cover and management factor for the land cover	crop.dat
USLE_P	P_{USLE}: USLE support practice factor	.mgt
SLSUBBSN	L_{hill}: Slope length (m)	.hru
SLOPE	*slp*: Average slope of the subbasin (% or m/m)	.hru
ROCK	*rock*: Percent rock in the first soil layer (%)	.sol

13.2 USLE

For comparative purposes, SWAT prints out sediment loadings calculated with USLE. ***These values are not used by the model, they are for comparison only***. The universal soil loss equation (Williams, 1995) is:

$$sed = 1.292 \cdot EI_{USLE} \cdot K_{USLE} \cdot C_{USLE} \cdot P_{USLE} \cdot LS_{USLE} \cdot CFRG \qquad\qquad 13.2.1$$

where *sed* is the sediment yield on a given day (metric tons/ha), EI_{USLE} is the rainfall erosion index (0.017 m-metric ton cm/(m^2 hr)), K_{USLE} is the USLE soil erodibility factor (0.013 metric ton m^2 hr/(m^3-metric ton cm)), C_{USLE} is the USLE cover and management factor, P_{USLE} is the USLE support practice factor, LS_{USLE} is the USLE topographic factor and *CFRG* is the coarse fragment factor. The factors other than EI_{USLE} are discussed in the preceeding sections.

13.2.1 RAINFALL ERODIBILITY INDEX

The value of EI_{USLE} for a given rainstorm is the product, total storm energy times the maximum 30 minute intensity. The storm energy indicates the volume of rainfall and runoff while the 30 minute intensity indicates the prolonged peak rates of detachment and runoff.

$$EI_{USLE} = E_{storm} \cdot I_{30} \qquad\qquad 13.2.2$$

where EI_{USLE} is the rainfall erosion index (0.017 m-metric ton cm/(m^2 hr)), E_{storm} is the total storm energy (0.0017 m-metric ton/m^2), and I_{30} is the maximum 30-minute intensity (mm/hr).

The energy of a rainstorm is a function of the amount of rain and of all the storm's component intensities. Because rainfall is provided to the model in daily totals, an assumption must be made about variation in rainfall intensity. The rainfall intensity variation with time is assumed to be exponentially distributed:

$$i_t = i_{mx} \cdot \exp\left(-\frac{t}{k_i}\right)$$ 13.2.3

where i_t is the rainfall intensity at time t (mm/hr), i_{mx} is the maximum rainfall intensity (mm/hr), t is the time (hr), and k_i is the decay constant for rainfall intensity (hr).

The USLE energy equation is

$$E_{storm} = \Delta R_{day} \cdot \left(12.1 + 8.9 \cdot \log_{10}\left[\frac{\Delta R_{day}}{\Delta t}\right]\right)$$ 13.2.4

where ΔR_{day} is the amount of rainfall during the time interval (mm H$_2$O), and Δt is the time interval (hr). This equation may be expressed analytically as:

$$E_{storm} = 12.1\int_0^\infty i_t dt + 8.9 \int_0^\infty i_t \log_{10} i_t dt$$ 13.2.5

Combining equation 13.2.5 and 13.2.3 and integrating gives the equation for estimating daily rainfall energy:

$$E_{storm} = \frac{R_{day}}{1000} \cdot \left(12.1 + 8.9 \cdot \left(\log_{10}[i_{mx}] - 0.434\right)\right)$$ 13.2.6

where R_{day} is the amount of precipitation falling on a given day (mm H$_2$O), and i_{mx} is the maximum rainfall intensity (mm/hr). To compute the maximum rainfall intensity, i_{mx}, equation 13.2.3 is integrated to give

$$R_{day} = i_{mx} \cdot k_i$$ 13.2.7

and

$$R_t = R_{day} \cdot \left(1 - \exp\left[-\frac{t}{k_i}\right]\right)$$ 13.2.8

where R_{day} is the amount of precipitation falling on a given day (mm H$_2$O), i_{mx} is the maximum rainfall intensity (mm/hr), k_i is the decay constant for rainfall intensity (hr), R_t is the amount of rain falling during a time interval (mm H$_2$O), and t is the time interval (hr). The maximum half-hour rainfall for the precipitation event is known:

$$R_{0.5} = \alpha_{0.5} \cdot R_{day}$$ 13.2.9

where $R_{0.5}$ is the maximum half-hour rainfall (mm H$_2$O), $\alpha_{0.5}$ is the maximum half-hour rainfall expressed as a fraction of daily rainfall, and R_{day} is the amount of precipitation falling on a given day (mm H$_2$O). Calculation of $\alpha_{0.5}$ is reviewed in Chapter 4. Substituting equation 13.2.9 and 13.2.7 into 13.2.8 and solving for the maximum intensity gives:

$$i_{mx} = -2 \cdot R_{day} \cdot \ln(1 - \alpha_{0.5})$$ 13.2.10

where i_{mx} is the maximum rainfall intensity (mm/hr), R_{day} is the amount of precipitation falling on a given day (mm H$_2$O), and $\alpha_{0.5}$ is the maximum half-hour rainfall expressed as a fraction of daily rainfall.

The maximum 30 minute intensity is calculated:

$$I_{30} = 2 \cdot \alpha_{0.5} \cdot R_{day}$$ 13.2.3

where I_{30} is the maximum 30-minute intensity (mm/hr), $\alpha_{0.5}$ is the maximum half-hour rainfall expressed as a fraction of daily rainfall, and R_{day} is the amount of precipitation falling on a given day (mm H$_2$O).

Table 13-6: SWAT input variables that pertain to USLE sediment yield.

Variable Name	Definition	Input File
USLE_K	K_{USLE}: USLE soil erodibility factor (0.013 metric ton m^2 hr/(m^3-metric ton cm))	.sol
USLE_C	$C_{USLE,mn}$: Minimum value for the cover and management factor for the land cover	crop.dat
USLE_P	P_{USLE}: USLE support practice factor	.mgt
SLSUBBSN	L_{hill}: Slope length (m)	.hru
SLOPE	slp: Average slope of the subbasin (% or m/m)	.hru
ROCK	$rock$: Percent rock in the first soil layer (%)	.sol

13.3 SNOW COVER EFFECTS

The erosive power of rain and runoff will be less when snow cover is present than when there is no snow cover. During periods when snow is present in an HRU, SWAT modifies the sediment yield using the following relationship:

$$sed = \frac{sed'}{\exp\left[\dfrac{3 \cdot SNO}{25.4}\right]}$$ 13.3.1

where sed is the sediment yield on a given day (metric tons), sed' is the sediment yield calculated with MUSLE (metric tons), and SNO is the water content of the snow cover (mm H_2O).

13.4 SEDIMENT LAG IN SURFACE RUNOFF

In large subbasins with a time of concentration greater than 1 day, only a portion of the surface runoff will reach the main channel on the day it is generated. SWAT incorporates a surface runoff storage feature to lag a portion of the surface runoff release to the main channel. Sediment in the surface runoff is lagged as well.

Once the sediment load in surface runoff is calculated, the amount of sediment released to the main channel is calculated:

$$sed = \left(sed' + sed_{stor,i-1}\right) \cdot \left(1 - \exp\left[\frac{-surlag}{t_{conc}}\right]\right)$$ 13.4.1

where sed is the amount of sediment discharged to the main channel on a given day (metric tons), sed' is the amount of sediment load generated in the HRU on a given day (metric tons), $sed_{stor,i-1}$ is the sediment stored or lagged from the previous day (metric tons), $surlag$ is the surface runoff lag coefficient, and t_{conc} is the time of concentration for the HRU (hrs).

The expression $\left(1 - \exp\left[\dfrac{-surlag}{t_{conc}}\right]\right)$ in equation 13.4.1 represents the

fraction of the total available sediment that will be allowed to enter the reach on any one day. Figure 13-1 plots values for this expression at different values for *surlag* and t_{conc}.
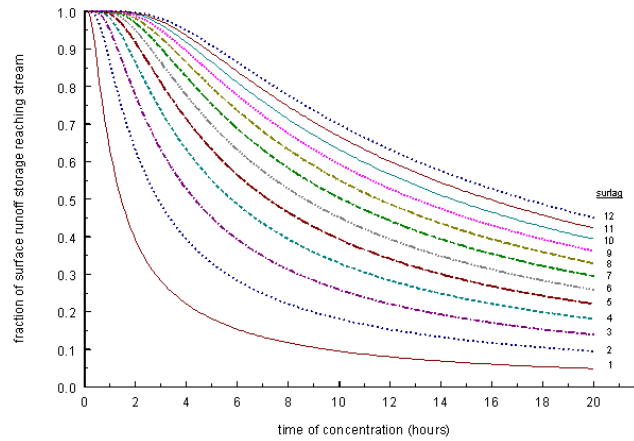

Figure 13-1: Influence of *surlag* and t_{conc} on fraction of surface runoff and sediment released.

Note that for a given time of concentration, as *surlag* decreases in value more sediment is held in storage.

Table 13-7: SWAT input variables that pertain to sediment lag calculations.

Variable Name	Definition	Input File
SURLAG	*surlag*: surface runoff lag coefficient	.bsn

13.5 SEDIMENT IN LATERAL & GROUNDWATER FLOW

SWAT allows the lateral and groundwater flow to contribute sediment to the main channel. The amount of sediment contributed by lateral and groundwater flow is calculated:

$$sed_{lat} = \frac{(Q_{lat} + Q_{gw}) \cdot area_{hru} \cdot conc_{sed}}{1000}$$ 13.5.1

where sed_{lat} is the sediment loading in lateral and groundwater flow (metric tons), Q_{lat} is the lateral flow for a given day (mm H$_2$O), Q_{gw} is the groundwater flow for

a given day (mm H$_2$O), *area$_{hru}$* is the area of the HRU (km^2), and *conc$_{sed}$* is the concentration of sediment in lateral and groundwater flow (mg/L).

Table 13-8: SWAT input variables that pertain to sediment lag calculations.

Variable Name	Definition	Input File
LAT_SED	*conc$_{sed}$*: Concentration of sediment in lateral and groundwater flow (mg/L)	.hru

13.6 NOMENCLATURE

C_{USLE} USLE cover and management factor
$C_{USLE,aa}$ Average annual C factor for the land cover
$C_{USLE,mn}$ Minimum value for the cover and management factor for the land cover
$CFRG$ Coarse fragment factor
E_{storm} Total storm energy (0.0017 m-metric ton/m^2),
EI_{USLE} Rainfall erosion index (0.017 m-metric ton cm/(m^2 hr))
I_{30} Maximum 30 minute intensity (mm/hr)
K_{USLE} USLE soil erodibility factor (0.013 metric ton m^2 hr/(m^3-metric ton cm))
L_{hill} Slope length (m)
LS_{USLE} USLE topographic factor
M Particle-size parameter for estimation of USLE K factor
OM Percent organic matter (%)
P_{USLE} USLE support practice factor
Q_{gw} Groundwater flow for a given day (mm H$_2$O)
Q_{lat} Lateral flow (mm H$_2$O)
Q_{surf} Surface runoff volume (mm H$_2$O/ha)
R_{day} Amount of rainfall on a given day (mm H$_2$O)
SNO Water content of the snow cover (mm H$_2$O)

$area_{hru}$ HRU area (ha or km^2)
c_{perm} Profile-permeability class
$c_{soilstr}$ Soil-structure code used in soil classification
$conc_{sed}$ Concentration of sediment in lateral and groundwater flow (mg/L)
f_{cl-si} Factor that gives low soil erodibility factors for soils with high clay to silt ratios
f_{csand} Factor that gives low soil erodibility factors for soils with high coarse-sand contents and high values for soils with little sand
f_{hisand} Factor that reduces soil erodibility for soils with extremely high sand contents
f_{orgc} Factor that reduces soil erodibility for soils with high organic carbon content
i_{mx} Maximum rainfall intensity (mm/hr)
i_t Rainfall intensity at time *t* (mm/hr)
k_i Decay constant for rainfall intensity (hr)
m Exponential term in USLE LS factor calculation
m_c Percent clay content (< 0.002 mm diameter particles)
m_s Percent sand content

m_{silt} Percent silt content (0.002-0.05 mm diameter particles)
m_{vfs} Percent very fine sand content (0.05-0.10 mm diameter particles)
$orgC_{ly}$ Amount of organic carbon in the layer (%)
q_{peak} Peak runoff rate (m³/s)
$rock$ Percent rock in soil layer (%)
rsd_{surf} Amount of residue on the soil surface (kg/ha)
sed Sediment yield on a given day (metric tons)
sed_{lat} Sediment loading in lateral and groundwater flow (metric tons)
$sed_{stor,i-1}$ Sediment stored or lagged from the previous day (metric tons)
slp Average slope of the subbasin (m/m)
$surlag$ Surface runoff lag coefficient
t Time (hr)
t_{conc} Time of concentration for a subbasin (hr)

$\alpha_{0.5}$ Maximum half-hour rainfall expressed as a fraction of daily rainfall
α_{hill} Angle of the slope

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CHAPTER 14

EQUATIONS: NUTRIENT TRANSPORT

The transport of nutrients from land areas into streams and water bodies is a normal result of soil weathering and erosion processes. However, excessive loading of nutrients into streams and water bodies will accelerate eutrophication and render the water unfit for human consumption. This chapter reviews the algorithms governing movement of mineral and organic forms of nitrogen and phosphorus from land areas to the stream network.

14.1 NITRATE MOVEMENT

Most soil minerals are negatively charged at normal pH and the net interaction with anions such as nitrate is a repulsion from particle surfaces. This repulsion is termed negative adsorption or anion exclusion.

Anions are excluded from the area immediately adjacent to mineral surfaces due to preferential attraction of cations to these sites. This process has a direct impact on the transport of anions through the soil for it effectively excludes anions from the slowest moving portion of the soil water volume found closest to the charged particle surfaces (Jury et al, 1991). In effect, the net pathway of the anion through the soil is shorter than it would be if all the soil water had to be used (Thomas and McMahon, 1972).

Nitrate may be transported with surface runoff, lateral flow or percolation. To calculate the amount of nitrate moved with the water, the concentration of nitrate in the mobile water is calculated. This concentration is then multiplied by the volume of water moving in each pathway to obtain the mass of nitrate lost from the soil layer.

The concentration of nitrate in the mobile water fraction is calculated:

$$conc_{NO3,mobile} = \frac{NO3_{ly} \cdot \exp\left[\dfrac{-w_{mobile}}{(1-\theta_e) \cdot SAT_{ly}}\right]}{w_{mobile}}$$ 14.1.2

where $conc_{NO3,mobile}$ is the concentration of nitrate in the mobile water for a given layer (kg N/mm H_2O), $NO3_{ly}$ is the amount of nitrate in the layer (kg N/ha), w_{mobile} is the amount of mobile water in the layer (mm H_2O), θ_e is the fraction of porosity from which anions are excluded, and SAT_{ly} is the saturated water content of the soil layer (mm H_2O). The amount of mobile water in the layer is the amount of water lost by surface runoff, lateral flow or percolation:

$$w_{mobile} = Q_{surf} + Q_{lat,ly} + w_{perc,ly} \qquad \text{for top 10 mm} \qquad 14.1.3$$

$$w_{mobile} = Q_{lat,ly} + w_{perc,ly} \qquad \text{for lower soil layers} \qquad 14.1.4$$

where w_{mobile} is the amount of mobile water in the layer (mm H_2O), Q_{surf} is the surface runoff generated on a given day (mm H_2O), $Q_{lat,ly}$ is the water discharged

from the layer by lateral flow (mm H_2O), and $w_{perc,ly}$ is the amount of water percolating to the underlying soil layer on a given day (mm H_2O). Surface runoff is allowed to interact with and transport nutrients from the top 10 mm of soil.

Nitrate removed in surface runoff is calculated:

$$NO3_{surf} = \beta_{NO3} \cdot conc_{NO3,mobile} \cdot Q_{surf} \qquad\qquad 14.1.5$$

where $NO3_{surf}$ is the nitrate removed in surface runoff (kg N/ha), β_{NO3} is the nitrate percolation coefficient, $conc_{NO3,mobile}$ is the concentration of nitrate in the mobile water for the top 10 mm of soil (kg N/mm H_2O), and Q_{surf} is the surface runoff generated on a given day (mm H_2O). The nitrate percolation coefficient allows the user to set the concentration of nitrate in surface runoff to a fraction of the concentration in percolate.

Nitrate removed in lateral flow is calculated:

$$NO3_{lat,ly} = \beta_{NO3} \cdot conc_{NO3,mobile} \cdot Q_{lat,ly} \qquad \text{for top 10 mm} \qquad 14.1.6$$

$$NO3_{lat,ly} = conc_{NO3,mobile} \cdot Q_{lat,ly} \qquad \text{for lower layers} \qquad 14.1.7$$

where $NO3_{lat,ly}$ is the nitrate removed in lateral flow from a layer (kg N/ha), β_{NO3} is the nitrate percolation coefficient, $conc_{NO3,mobile}$ is the concentration of nitrate in the mobile water for the layer (kg N/mm H_2O), and $Q_{lat,ly}$ is the water discharged from the layer by lateral flow (mm H_2O).

Nitrate moved to the underlying layer by percolation is calculated:

$$NO3_{perc,ly} = conc_{NO3,mobile} \cdot w_{perc,ly} \qquad\qquad 14.1.8$$

where $NO3_{perc,ly}$ is the nitrate moved to the underlying layer by percolation (kg N/ha), $conc_{NO3,mobile}$ is the concentration of nitrate in the mobile water for the layer (kg N/mm H_2O), and $w_{perc,ly}$ is the amount of water percolating to the underlying soil layer on a given day (mm H_2O).

Table 14-1: SWAT input variables that pertain to nitrate transport.

Variable Name	Definition	Input File
ANION_EXCL	θ_e: Fraction of porosity from which anions are excluded	.sol
NPERCO	β_{NO3}: Nitrate percolation coefficient	.bsn

14.2 ORGANIC N IN SURFACE RUNOFF

Organic N attached to soil particles may be transported by surface runoff to the main channel. This form of nitrogen is associated with the sediment loading from the HRU and changes in sediment loading will be reflected in the organic nitrogen loading. The amount of organic nitrogen transported with sediment to the stream is calculated with a loading function developed by McElroy et al. (1976) and modified by Williams and Hann (1978).

$$orgN_{surf} = 0.001 \cdot conc_{orgN} \cdot \frac{sed}{area_{hru}} \cdot \varepsilon_{N:sed} \qquad 14.2.1$$

where $orgN_{surf}$ is the amount of organic nitrogen transported to the main channel in surface runoff (kg N/ha), $conc_{orgN}$ is the concentration of organic nitrogen in the top 10 mm (g N/ metric ton soil), sed is the sediment yield on a given day (metric tons), $area_{hru}$ is the HRU area (ha), and $\varepsilon_{N:sed}$ is the nitrogen enrichment ratio.

The concentration of organic nitrogen in the soil surface layer, $conc_{orgN}$, is calculated:

$$conc_{orgN} = 100 \cdot \frac{\left(orgN_{frsh,surf} + orgN_{sta,surf} + orgN_{act,surf}\right)}{\rho_b \cdot depth_{surf}} \qquad 14.2.2$$

where $orgN_{frsh,surf}$ is nitrogen in the fresh organic pool in the top 10mm (kg N/ha), $orgN_{sta,surf}$ is nitrogen in the stable organic pool (kg N/ha), $orgN_{act,surf}$ is nitrogen in the active organic pool in the top 10 mm (kg N/ha), ρ_b is the bulk density of the first soil layer (Mg/m^3), and $depth_{surf}$ is the depth of the soil surface layer (10 mm).

14.2.1 ENRICHMENT RATIO

As surface runoff flows over the soil surface, part of the water's energy is used to pick up and transport soil particles. The smaller particles weigh less and are more easily transported than coarser particles. When the particle size distribution of the transported sediment is compared to that of the soil surface layer, the sediment load to the main channel has a greater proportion of clay sized particles. In other words, the sediment load is enriched in clay particles. Organic

nitrogen in the soil is attached primarily to colloidal (clay) particles, so the sediment load will also contain a greater proportion or concentration of organic N than that found in the soil surface layer.

The enrichment ratio is defined as the ratio of the concentration of organic nitrogen transported with the sediment to the concentration in the soil surface layer. SWAT will calculate an enrichment ratio for each storm event, or allow the user to define a particular enrichment ratio for organic nitrogen that is used for all storms during the simulation. To calculate the enrichment ratio, SWAT uses a relationship described by Menzel (1980) in which the enrichment ratio is logarithmically related to sediment concentration. The equation used to calculate the nitrogen enrichment ratio, $\varepsilon_{N:sed}$, for each storm event is:

$$\varepsilon_{N:sed} = 0.78 \cdot \left(conc_{sed,surq}\right)^{-0.2468} \qquad 14.2.3$$

where $conc_{sed,surq}$ is the concentration of sediment in surface runoff (Mg sed/m^3 H$_2$O). The concentration of sediment in surface runoff is calculated:

$$conc_{sed,surq} = \frac{sed}{10 \cdot area_{hru} \cdot Q_{surf}} \qquad 14.2.4$$

where sed is the sediment yield on a given day (metric tons), $area_{hru}$ is the HRU area (ha), and $Q_{,surf}$ is the amount of surface runoff on a given day (mm H$_2$O).

Table 14-2: SWAT input variables that pertain to organic N loading.

Variable Name	Definition	Input File
SOL_BD	ρ_b: Bulk density (Mg/m^3)	.sol
ERORGN	$\varepsilon_{N:sed}$: Organic nitrogen enrichment ratio	.hru

14.3 SOLUBLE PHOSPHORUS MOVEMENT

The primary mechanism of phosphorus movement in the soil is by diffusion. Diffusion is the migration of ions over small distances (1-2 mm) in the soil solution in response to a concentration gradient. Due to the low mobility of solution phosphorus, surface runoff will only partially interact with the solution P stored in the top 10 mm of soil. The amount of solution P transported in surface runoff is:

$$P_{surf} = \frac{P_{solution,surf} \cdot Q_{surf}}{\rho_b \cdot depth_{surf} \cdot k_{d,surf}}$$ 14.3.1

where P_{surf} is the amount of soluble phosphorus lost in surface runoff (kg P/ha), $P_{solution,surf}$ is the amount of phosphorus in solution in the top 10 mm (kg P/ha), $Q_{,surf}$ is the amount of surface runoff on a given day (mm H_2O), ρ_b is the bulk density of the top 10 mm (Mg/m^3) (assumed to be equivalent to bulk density of first soil layer), $depth_{surf}$ is the depth of the "surface" layer (10 mm), and $k_{d,surf}$ is the phosphorus soil partitioning coefficient (m^3/Mg). The phosphorus soil partitioning coefficient is the ratio of the soluble phosphorus concentration in the surface 10 mm of soil to the concentration of soluble phosphorus in surface runoff.

Table 14-3: SWAT input variables that pertain to soluble P runoff.

Variable Name	Definition	Input File
SOL_BD	ρ_b: Bulk density (Mg/m^3)	.sol
PHOSKD	$k_{d,surf}$: Phosphorus soil partitioning coefficient (m^3/Mg)	.bsn

14.4 ORGANIC & MINERAL P ATTACHED TO SEDIMENT IN SURFACE RUNOFF

Organic and mineral P attached to soil particles may be transported by surface runoff to the main channel. This form of phosphorus is associated with the sediment loading from the HRU and changes in sediment loading will be reflected in the loading of these forms of phophorus. The amount of phosphorus transported with sediment to the stream is calculated with a loading function developed by McElroy et al. (1976) and modified by Williams and Hann (1978).

$$sedP_{surf} = 0.001 \cdot conc_{sedP} \cdot \frac{sed}{area_{hru}} \cdot \varepsilon_{P:sed}$$ 14.4.1

where $sedP_{surf}$ is the amount of phosphorus transported with sediment to the main channel in surface runoff (kg P/ha), $conc_{sedP}$ is the concentration of phosphorus attached to sediment in the top 10 mm (g P/ metric ton soil), sed is the sediment yield on a given day (metric tons), $area_{hru}$ is the HRU area (ha), and $\varepsilon_{P:sed}$ is the phosphorus enrichment ratio.

The concentration of phosphorus attached to sediment in the soil surface layer, $conc_{sedP}$, is calculated:

$$conc_{sedP} = 100 \cdot \frac{\left(minP_{act,surf} + minP_{sta,surf} + orgP_{hum,surf} + orgP_{frsh,surf}\right)}{\rho_b \cdot depth_{surf}}$$ 14.4.2

where $minP_{act,surf}$ is the amount of phosphorus in the active mineral pool in the top 10 mm (kg P/ha), $minP_{sta,surf}$ is the amount of phosphorus in the stable mineral pool in the top 10 mm (kg P/ha), $orgP_{hum,surf}$ is the amount of phosphorus in humic organic pool in the top 10 mm (kg P/ha), $orgP_{frsh,surf}$ is the amount of phosphorus in the fresh organic pool in the top 10 mm (kg P/ha), ρ_b is the bulk density of the first soil layer (Mg/m^3), and $depth_{surf}$ is the depth of the soil surface layer (10 mm).

14.4.1 ENRICHMENT RATIO

The enrichment ratio is defined as the ratio of the concentration of phosphorus transported with the sediment to the concentration of phosphorus in the soil surface layer. SWAT will calculate an enrichment ratio for each storm event, or allow the user to define a particular enrichment ratio for phosphorus attached to sediment that is used for all storms during the simulation. To calculate the enrichment ratio, SWAT uses a relationship described by Menzel (1980) in which the enrichment ratio is logarithmically related to sediment concentration. The equation used to calculate the phosphorus enrichment ratio, $\varepsilon_{P:sed}$, for each storm event is:

$$\varepsilon_{P:sed} = 0.78 \cdot \left(conc_{sed,surq}\right)^{-0.2468}$$ 14.4.3

where $conc_{sed,surq}$ is the concentration of sediment in surface runoff (Mg sed/m^3 H$_2$O). The concentration of sediment in surface runoff is calculated:

$$conc_{sed,surq} = \frac{sed}{10 \cdot area_{hru} \cdot Q_{surf}}$$ 14.4.4

where sed is the sediment yield on a given day (metric tons), $area_{hru}$ is the HRU area (ha), and Q_{surf} is the amount of surface runoff on a given day (mm H$_2$O).

Table 14-4: SWAT input variables that pertain to loading of P attached to sediment.

Variable Name	Definition	Input File
SOL_BD	ρ_b: Bulk density (Mg/m^3)	.sol
ERORGP	$\varepsilon_{P:sed}$: Phosphorus enrichment ratio	.hru

14.5 NUTRIENT LAG IN SURFACE RUNOFF AND LATERAL FLOW

In large subbasins with a time of concentration greater than 1 day, only a portion of the surface runoff and lateral flow will reach the main channel on the day it is generated. SWAT incorporates a storage feature to lag a portion of the surface runoff and lateral flow release to the main channel. Nutrients in the surface runoff and lateral flow are lagged as well.

Once the nutrient load in surface runoff and lateral flow is determined, the amount of nutrients released to the main channel is calculated:

$$NO3_{surf} = \left(NO3'_{surf} + NO3_{surstor,i-1}\right)\cdot\left(1 - \exp\left[\frac{-surlag}{t_{conc}}\right]\right) \qquad 14.5.1$$

$$NO3_{lat} = \left(NO3'_{lat} + NO3_{latstor,i-1}\right)\cdot\left(1 - \exp\left[\frac{-1}{TT_{lat}}\right]\right) \qquad 14.5.2$$

$$orgN_{surf} = \left(orgN'_{surf} + orgN_{stor,i-1}\right)\cdot\left(1 - \exp\left[\frac{-surlag}{t_{conc}}\right]\right) \qquad 14.5.3$$

$$P_{surf} = \left(P'_{surf} + P_{stor,i-1}\right)\cdot\left(1 - \exp\left[\frac{-surlag}{t_{conc}}\right]\right) \qquad 14.5.4$$

$$sedP_{surf} = \left(sedP'_{surf} + sedP_{stor,i-1}\right)\cdot\left(1 - \exp\left[\frac{-surlag}{t_{conc}}\right]\right) \qquad 14.5.5$$

where $NO3_{surf}$ is the amount of nitrate discharged to the main channel in surface runoff on a given day (kg N/ha), $NO3'_{surf}$ is the amount of surface runoff nitrate generated in the HRU on a given day (kg N/ha), $NO3_{surstor,i-1}$ is the surface runoff nitrate stored or lagged from the previous day (kg N/ha), $NO3_{lat}$ is the amount of nitrate discharged to the main channel in lateral flow on a given day (kg N/ha),

$NO3'_{lat}$ is the amount of lateral flow nitrate generated in the HRU on a given day (kg N/ha), $NO3_{latstor,i-1}$ is the lateral flow nitrate stored or lagged from the previous day (kg N/ha), $orgN_{surf}$ is the amount of organic N discharged to the main channel in surface runoff on a given day (kg N/ha), $orgN'_{surf}$ is the organic N loading generated in the HRU on a given day (kg N/ha), $orgN_{stor,i-1}$ is the organic N stored or lagged from the previous day (kg N/ha), P_{surf} is the amount of solution P discharged to the main channel in surface runoff on a given day (kg P/ha), P'_{surf} is the amount of solution P loading generated in the HRU on a given day (kg P/ha), $P_{stor,i-1}$ is the solution P loading stored or lagged from the previous day (kg P/ha), $sedP_{surf}$ is the amount of sediment-attached P discharged to the main channel in surface runoff on a given day (kg P/ha), $sedP'_{surf}$ is the amount of sediment-attached P loading generated in the HRU on a given day (kg P/ha), $sedP_{stor,i-1}$ is the sediment-attached P stored or lagged from the previous day (kg P/ha), $surlag$ is the surface runoff lag coefficient, t_{conc} is the time of concentration for the HRU (hrs) and TT_{lag} is the lateral flow travel time (days).

Table 14-5: SWAT input variables that pertain to nutrient lag calculations.

Variable Name	Definition	Input File
SURLAG	$surlag$: surface runoff lag coefficient	.bsn
LAT_TTIME	TT_{lag}: Lateral flow travel time (days)	.hru

14.6 NOMENCLATURE

$NO3_{lat,ly}$ Nitrate removed in lateral flow from a layer (kg N/ha)

$NO3'_{lat}$ Amount of lateral flow nitrate generated in HRU on a given day (kg N/ha)

$NO3_{latstor,i-1}$ Lateral flow nitrate stored or lagged from the previous day (kg N/ha)

$NO3_{ly}$ Amount of nitrate in the layer (kg N/ha)

$NO3_{perc,ly}$ Nitrate moved to the underlying layer by percolation (kg N/ha)

$NO3_{surf}$ Nitrate removed in surface runoff (kg N/ha)

$NO3'_{surf}$ Amount of surface runoff nitrate generated in HRU on a given day (kg N/ha)

$NO3_{surstor,i-1}$ Surface runoff nitrate stored or lagged from the previous day (kg N/ha)

$P_{solution,surf}$ Amount of phosphorus in solution in the top 10 mm (kg P/ha)

$P_{stor,i-1}$ Solution P loading stored or lagged from the previous day (kg P/ha)

P_{surf} Amount of soluble phosphorus lost in surface runoff (kg P/ha)

P'_{surf} Amount of solution P loading generated in HRU on a given day (kg P/ha)

Q_{lat} Lateral flow from soil layer (mm H_2O)

Q_{surf} Accumulated runoff or rainfall excess (mm H_2O)

SAT_{ly} Saturated water content of the soil layer (mm H_2O)

TT_{lag} Lateral flow travel time (days)

$area_{hru}$ HRU area (ha)

$conc_{NO3,mobile}$ Concentration of nitrate in the mobile water for a given layer (kg N/mm H_2O)

$conc_{orgN}$ Concentration of organic nitrogen in the soil surface top 10 mm (g N/ metric ton soil)

$conc_{sed,surq}$ Concentration of sediment in surface runoff (Mg sed/m^3 H_2O)

$conc_{sedP}$ Concentration of phosphorus attached to sediment in the top 10 mm (g P/ metric ton soil)

$depth_{surf}$ Depth of the "surface" layer (10 mm)

$k_{d,surf}$ Phosphorus soil partitioning coefficient (m^3/Mg)

$minP_{act,ly}$ Amount of phosphorus in the active mineral pool (kg P/ha)

$minP_{sta,ly}$ Amount of phosphorus in the stable mineral pool (kg P/ha)

$orgN_{act,ly}$ Nitrogen in the active organic pool (mg/kg or kg N/ha)

$orgN_{frsh,surf}$ Nitrogen in the fresh organic pool in the top 10mm (kg N/ha)

$orgN_{sta,ly}$ Nitrogen in the stable organic pool (mg/kg or kg N/ha)

$orgN_{stor,i-1}$ Surface runoff organic N stored or lagged from the previous day (kg N/ha)

$orgN_{surf}$ Amount of organic nitrogen transport to the main channel in surface runoff (kg N/ha)

$orgN'_{surf}$ Amount of surface runoff organic N generated in HRU on a given day (kg N/ha)

$orgP_{frsh,ly}$ Phosphorus in the fresh organic pool in layer ly (kg P/ha)

$orgP_{hum,ly}$ Amount of phosphorus in humic organic pool in the layer (kg P/ha)

sed Sediment yield on a given day (metric tons)

$sedP_{stor,i-1}$ Sediment-attached P stored or lagged from the previous day (kg P/ha)

$sedP_{surf}$ Amount of phosphorus transported with sediment to the main channel in surface runoff (kg P/ha)

$sedP'_{surf}$ Amount of sediment-attached P loading generated in HRU on a given day (kg P/ha)

$surlag$ Surface runoff lag coefficient

t_{conc} Time of concentration for a subbasin (hr)

w_{mobile} Amount of mobile water in the layer (mm H_2O)

$w_{perc,ly}$ Amount of water percolating to the underlying soil layer on a given day (mm H_2O)

β_{NO3} Nitrate percolation coefficient

θ_e Fraction of porosity from which anions are excluded

$\varepsilon_{N:sed}$ Nitrogen enrichment ratio

$\varepsilon_{P:sed}$ Phosphorus enrichment ratio

ρ_b Bulk density (Mg/m^3)

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CHAPTER **15**

EQUATIONS: PESTICIDE TRANSPORT

The transport of pesticide from land areas into streams and water bodies is a result of soil weathering and erosion processes. Excessive loading of pesticides in streams and water bodies can produce toxic conditions that harm aquatic life and render the water unfit for human consumption. This chapter reviews the algorithms governing movement of soluble and sorbed forms of pesticide from land areas to the stream network. Pesticide transport algorithms in SWAT were taken from EPIC (Williams, 1995).

15.1 PHASE DISTRIBUTION OF PESTICIDE

Pesticide in the soil environment can be transported in solution or attached to sediment. The partitioning of a pesticide between the solution and soil phases is defined by the soil adsorption coefficient for the pesticide. The soil adsorption coefficient is the ratio of the pesticide concentration in the soil or solid phase to the pesticide concentration in the solution or liquid phase:

$$K_p = \frac{C_{solidphase}}{C_{solution}}$$ 15.1.1

where K_p is the soil adsorption coefficient $((mg/kg)/(mg/L)$ or $m^3/ton)$, $C_{solidphase}$ is the concentration of the pesticide sorbed to the solid phase (mg chemical/kg solid material or g/ton), and $C_{solution}$ is the concentration of the pesticide in solution (mg chemical/L solution or g/ton). The definition of the soil adsorption coefficient in equation 15.1.1 assumes that the pesticide sorption process is linear with concentration and instantaneously reversible.

Because the partitioning of pesticide is dependent upon the amount of organic material in the soil, the soil adsorption coefficient input to the model is normalized for soil organic carbon content. The relationship between the soil adsorption coefficient and the soil adsorption coefficient normalized for soil organic carbon content is:

$$K_p = K_{oc} \cdot \frac{orgC}{100}$$ 15.1.2

where K_p is the soil adsorption coefficient $((mg/kg)/(mg/L))$, K_{oc} is the soil adsorption coefficient normalized for soil organic carbon content $((mg/kg)/(mg/L)$ or $m^3/ton)$, and $orgC$ is the percent organic carbon present in the soil.

Table 15-1: SWAT input variables that pertain to pesticide phase partitioning.

Variable Name	Definition	Input File
SOL_CBN	$orgC_{ly}$: Amount of organic carbon in the layer (%)	.sol
SKOC	K_{oc}: Soil adsorption coefficient normalized for soil organic carbon content (ml/g or (mg/kg)/(mg/L) or L/kg)	pest.dat

15.2 MOVEMENT OF SOLUBLE PESTICIDE

Pesticide in the soluble phase may be transported with surface runoff, lateral flow or percolation. The change in the amount of pesticide contained in a soil layer due to transport in solution with flow is a function of time, concentration and amount of flow:

$$\frac{dpst_{s,ly}}{dt} = 0.01 \cdot C_{solution} \cdot w_{mobile} \qquad\qquad 15.2.1$$

where $pst_{s,ly}$ is the amount of pesticide in the soil layer (kg pst/ha), $C_{solution}$ is the pesticide concentration in solution (mg/L or g/ton), and w_{mobile} is the amount of mobile water on a given day (mm H_2O). The amount of mobile water in the layer is the amount of water lost by surface runoff, lateral flow or percolation:

$$w_{mobile} = Q_{surf} + Q_{lat,surf} + w_{perc,surf} \qquad \text{for top 10 mm} \qquad 15.2.2$$

$$w_{mobile} = Q_{lat,ly} + w_{perc,ly} \qquad\qquad \text{for lower soil layers} \qquad 15.2.3$$

where w_{mobile} is the amount of mobile water in the layer (mm H_2O), Q_{surf} is the surface runoff generated on a given day (mm H_2O), $Q_{lat,ly}$ is the water discharged from the layer by lateral flow (mm H_2O), and $w_{perc,ly}$ is the amount of water percolating to the underlying soil layer on a given day (mm H_2O).

The total amount of pesticide in the soil layer is the sum of the adsorbed and dissolved phases:

$$pst_{s,ly} = 0.01 \cdot \left(C_{solution} \cdot SAT_{ly} + C_{solidphase} \cdot \rho_b \cdot depth_{ly} \right) \qquad 15.2.4$$

where $pst_{s,ly}$ is the amount of pesticide in the soil layer (kg pst/ha), $C_{solution}$ is the pesticide concentration in solution (mg/L or g/ton), SAT_{ly} is the amount of water in the soil layer at saturation (mm H_2O), $C_{solidphase}$ is the concentration of the pesticide sorbed to the solid phase (mg/kg or g/ton), ρ_b is the bulk density of the soil layer (Mg/m^3), and $depth_{ly}$ is the depth of the soil layer (mm). Rearranging equation 15.1.1 to solve for $C_{solidphase}$ and substituting into equation 15.2.4 yields:

$$pst_{s,ly} = 0.01 \cdot \left(C_{solution} \cdot SAT_{ly} + C_{solution} \cdot K_p \cdot \rho_b \cdot depth_{ly} \right) \qquad 15.2.5$$

which rearranges to

$$C_{solution} = \frac{pst_{s,ly}}{0.01 \cdot \left(SAT_{ly} + K_p \cdot \rho_b \cdot depth_{ly}\right)}$$ 15.2.6

Combining equation 15.2.6 with equation 15.2.1 yields

$$\frac{dpst_{s,ly}}{dt} = \frac{pst_{s,ly} \cdot w_{mobile}}{\left(SAT_{ly} + K_p \cdot \rho_b \cdot depth_{ly}\right)}$$ 15.2.7

Integration of equation 15.2.7 gives

$$pst_{s,ly,t} = pst_{s,ly,o} \cdot \exp\left[\frac{-w_{mobile}}{\left(SAT_{ly} + K_p \cdot \rho_b \cdot depth_{ly}\right)}\right]$$ 15.2.8

where $pst_{s,ly,t}$ is the amount of pesticide in the soil layer at time t (kg pst/ha), $pst_{s,ly,o}$ is the initial amount of pesticide in the soil layer (kg pst/ha), w_{mobile} is the amount of mobile water in the layer (mm H$_2$O), SAT_{ly} is the amount of water in the soil layer at saturation (mm H$_2$O), K_p is the soil adsorption coefficient ((mg/kg)/(mg/L)), ρ_b is the bulk density of the soil layer (Mg/m^3), and $depth_{ly}$ is the depth of the soil layer (mm).

To obtain the amount of pesticide removed in solution with the flow, the final amount of pesticide is subtracted from the initial amount of pesticide:

$$pst_{flow} = pst_{s,ly,o} \cdot \left(1 - \exp\left[\frac{-w_{mobile}}{\left(SAT_{ly} + K_p \cdot \rho_b \cdot depth_{ly}\right)}\right]\right)$$ 15.2.9

where pst_{flow} is the amount of pesticide removed in the flow (kg pst/ha) and all other terms were previously defined.

The pesticide concentration in the mobile water is calculated:

$$conc_{pst,flow} = \min\begin{cases} pst_{flow} / w_{mobile} \\ \\ pst_{sol} / 100. \end{cases}$$ 15.2.10

where $conc_{pst,flow}$ is the concentration of pesticide in the mobile water (kg pst/ha-mm H$_2$O), pst_{flow} is the amount of pesticide removed in the flow (kg pst/ha), w_{mobile} is the amount of mobile water in the layer (mm H$_2$O), and pst_{sol} is the solubility of the pesticide in water (mg/L).

Pesticide moved to the underlying layer by percolation is calculated:

$$pst_{perc,ly} = conc_{pst,flow} \cdot w_{perc,ly}$$ 15.2.11

where $pst_{perc,ly}$ is the pesticide moved to the underlying layer by percolation (kg pst/ha), $conc_{pst,flow}$ is the concentration of pesticide in the mobile water for the layer (kg pst/mm H_2O), and $w_{perc,ly}$ is the amount of water percolating to the underlying soil layer on a given day (mm H_2O).

Pesticide removed in lateral flow is calculated:

$$pst_{lat,surf} = \beta_{pst} \cdot conc_{pst,flow} \cdot Q_{lat,surf} \qquad \text{for top 10 mm} \qquad 15.2.12$$

$$pst_{lat,ly} = conc_{pst,flow} \cdot Q_{lat,ly} \qquad \text{for lower layers} \qquad 15.2.13$$

where $pst_{lat,ly}$ is the pesticide removed in lateral flow from a layer (kg pst/ha), β_{pst} is the pesticide percolation coefficient, $conc_{pst,flow}$ is the concentration of pesticide in the mobile water for the layer (kg pst/mm H_2O), and $Q_{lat,ly}$ is the water discharged from the layer by lateral flow (mm H_2O). The pesticide percolation coefficient allows the user to set the concentration of pesticide in runoff and lateral flow from the top 10 mm to a fraction of the concentration in percolate.

Pesticide removed in surface runoff is calculated:

$$pst_{surf} = \beta_{pst} \cdot conc_{pst,flow} \cdot Q_{surf} \qquad\qquad 15.2.14$$

where pst_{surf} is the pesticide removed in surface runoff (kg pst/ha), β_{pst} is the pesticide percolation coefficient, $conc_{pst,flow}$ is the concentration of pesticide in the mobile water for the top 10 mm of soil (kg pst/mm H_2O), and Q_{surf} is the surface runoff generated on a given day (mm H_2O).

Table 15-2: SWAT input variables that pertain to pesticide transport in solution.

Variable Name	Definition	Input File
SOL_BD	ρ_b: Soil bulk density (Mg m^{-3})	.sol
WSOL	pst_{sol}: Solubility of the pesticide in water (mg/L)	pest.dat
PERCOP	β_{pst}: Pesticide percolation coefficient	.bsn

15.3 TRANSPORT OF SORBED PESTICIDE

Pesticide attached to soil particles may be transported by surface runoff to the main channel. This phase of pesticide is associated with the sediment loading from the HRU and changes in sediment loading will be reflected in the loading of sorbed pesticide. The amount of pesticide transported with sediment to the stream is calculated with a loading function developed by McElroy et al. (1976) and modified by Williams and Hann (1978).

$$pst_{sed} = 0.001 \cdot C_{solidphase} \cdot \frac{sed}{area_{hru}} \cdot \varepsilon_{pst:sed} \qquad 15.3.1$$

where pst_{sed} is the amount of sorbed pesticide transported to the main channel in surface runoff (kg pst/ha), $C_{solidphase}$ is the concentration of pesticide on sediment in the top 10 mm (g pst/ metric ton soil), sed is the sediment yield on a given day (metric tons), $area_{hru}$ is the HRU area (ha), and $\varepsilon_{pst:sed}$ is the pesticide enrichment ratio.

The total amount of pesticide in the soil layer is the sum of the adsorbed and dissolved phases:

$$pst_{s,ly} = 0.01 \cdot \left(C_{solution} \cdot SAT_{ly} + C_{solidphase} \cdot \rho_b \cdot depth_{ly} \right) \qquad 15.3.2$$

where $pst_{s,ly}$ is the amount of pesticide in the soil layer (kg pst/ha), $C_{solution}$ is the pesticide concentration in solution (mg/L or g/ton), SAT_{ly} is the amount of water in the soil layer at saturation (mm H$_2$O), $C_{solidphase}$ is the concentration of the pesticide sorbed to the solid phase (mg/kg or g/ton), ρ_b is the bulk density of the soil layer (Mg/m^3), and $depth_{ly}$ is the depth of the soil layer (mm). Rearranging equation 15.1.1 to solve for $C_{solution}$ and substituting into equation 15.3.2 yields:

$$pst_{s,ly} = 0.01 \cdot \left(\frac{C_{solidphase}}{K_p} \cdot SAT_{ly} + C_{solidphase} \cdot \rho_b \cdot depth_{ly} \right) \qquad 15.3.3$$

which rearranges to

$$C_{solidphase} = \frac{100 \cdot K_p \cdot pst_{s,ly}}{\left(SAT_{ly} + K_p \cdot \rho_b \cdot depth_{ly} \right)} \qquad 15.3.4$$

where $C_{solidphase}$ is the concentration of the pesticide sorbed to the solid phase (mg/kg or g/ton), K_p is the soil adsorption coefficient ((mg/kg)/(mg/L) or m^3/ton)

$pst_{s,ly}$ is the amount of pesticide in the soil layer (kg pst/ha), SAT_{ly} is the amount of water in the soil layer at saturation (mm H$_2$O), , ρ_b is the bulk density of the soil layer (Mg/m^3), and $depth_{ly}$ is the depth of the soil layer (mm).

15.3.1 ENRICHMENT RATIO

As surface runoff flows over the soil surface, part of the water's energy is used to pick up and transport soil particles. The smaller particles weigh less and are more easily transported than coarser particles. When the particle size distribution of the transported sediment is compared to that of the soil surface layer, the sediment load to the main channel has a greater proportion of clay sized particles. In other words, the sediment load is enriched in clay particles. The sorbed phase of pesticide in the soil is attached primarily to colloidal (clay) particles, so the sediment load will also contain a greater proportion or concentration of pesticide than that found in the soil surface layer.

The enrichment ratio is defined as the ratio of the concentration of sorbed pesticide transported with the sediment to the concentration in the soil surface layer. SWAT will calculate an enrichment ratio for each storm event, or allow the user to define a particular enrichment ratio for sorbed pesticide that is used for all storms during the simulation. To calculate the enrichment ratio, SWAT uses a relationship described by Menzel (1980) in which the enrichment ratio is logarithmically related to sediment concentration. The equation used to calculate the pesticide enrichment ratio, $\varepsilon_{pst:sed}$, for each storm event is:

$$\varepsilon_{pst:sed} = 0.78 \cdot \left(conc_{sed,surq}\right)^{-0.2468} \tag{15.3.5}$$

where $conc_{sed,surq}$ is the concentration of sediment in surface runoff (Mg sed/m^3 H$_2$O). The concentration of sediment in surface runoff is calculated:

$$conc_{sed,surq} = \frac{sed}{10 \cdot area_{hru} \cdot Q_{surf}} \tag{15.3.6}$$

where sed is the sediment yield on a given day (metric tons), $area_{hru}$ is the HRU area (ha), and Q_{surf} is the amount of surface runoff on a given day (mm H$_2$O).

Table 15-3: SWAT input variables that pertain to sorbed pesticide loading.

Variable Name	Definition	Input File
SOL_BD	ρ_b: Bulk density (Mg/m^3)	.sol
PSTENR	$\varepsilon_{pst:sed}$: Pesticide enrichment ratio	.chm

15.4 PESTICIDE LAG IN
SURFACE RUNOFF AND LATERAL FLOW

In large subbasins with a time of concentration greater than 1 day, only a portion of the surface runoff and lateral flow will reach the main channel on the day it is generated. SWAT incorporates a storage feature to lag a portion of the surface runoff and lateral flow release to the main channel. Pesticides in the surface runoff and lateral flow are lagged as well.

Once the pesticide load in surface runoff and lateral flow is determined, the amount of pesticide released to the main channel is calculated:

$$pst_{surf} = \left(pst'_{surf} + pst_{surstor,i-1}\right) \cdot \left(1 - \exp\left[\frac{-surlag}{t_{conc}}\right]\right) \qquad 15.4.1$$

$$pst_{lat} = \left(pst'_{lat} + pst_{latstor,i-1}\right) \cdot \left(1 - \exp\left[\frac{-1}{TT_{lat}}\right]\right) \qquad 15.4.2$$

$$pst_{sed} = \left(pst'_{sed} + pst_{sedstor,i-1}\right) \cdot \left(1 - \exp\left[\frac{-surlag}{t_{conc}}\right]\right) \qquad 15.4.3$$

where pst_{surf} is the amount of soluble pesticide discharged to the main channel in surface runoff on a given day (kg pst/ha), pst'_{surf} is the amount of surface runoff soluble pesticide generated in HRU on a given day (kg pst/ha), $pst_{surstor,i-1}$ is the surface runoff soluble pesticide stored or lagged from the previous day (kg pst/ha), pst_{lat} is the amount of soluble pesticide discharged to the main channel in lateral flow on a given day (kg pst/ha), pst'_{lat} is the amount of lateral flow soluble pesticide generated in HRU on a given day (kg pst/ha), $pst_{latstor,i-1}$ is the lateral flow pesticide stored or lagged from the previous day (kg pst/ha), pst_{sed} is the amount of sorbed pesticide discharged to the main channel in surface runoff on a

given day (kg pst/ha), pst'_{sed} is the sorbed pesticide loading generated in HRU on a given day (kg pst/ha), $pst_{sedstor,i-1}$ is the sorbed pesticide stored or lagged from the previous day (kg pst/ha), *surlag* is the surface runoff lag coefficient, t_{conc} is the time of concentration for the HRU (hrs) and TT_{lag} is the lateral flow travel time (days).

Table 15-4: SWAT input variables that pertain to pesticide lag calculations.

Variable Name	Definition	Input File
SURLAG	*surlag*: surface runoff lag coefficient	.bsn
LAT_TTIME	TT_{lag}: Lateral flow travel time (days)	.hru

15.5 NOMENCLATURE

$C_{solidphase}$ Concentration of the pesticide sorbed to the solid phase (mg/kg or g/ton)
$C_{solution}$ Concentration of the pesticide in solution (mg/L or g/ton)
K_{oc} Soil adsorption coefficient normalized for soil organic carbon content (ml/g or (mg/kg)/(mg/L) or L/kg)
K_p Soil adsorption coefficient ((mg/kg)/(mg/L))
Q_{lat} Lateral flow from soil layer (mm H_2O)
Q_{surf} Accumulated runoff or rainfall excess (mm H_2O)
SAT_{ly} Soil water content of layer *ly* at saturation (mm H_2O)
TT_{lag} Lateral flow travel time (days)

$area_{hru}$ HRU area (ha)
$conc_{pst,flow}$ Concentration of pesticide in the mobile water (kg pst/ha-mm H_2O)
$conc_{sed,surq}$ Concentration of sediment in surface runoff (Mg sed/m^3 H_2O)
$depth_{ly}$ Depth of the soil layer (mm)
$orgC_{ly}$ Amount of organic carbon in the layer (%)
pst_{flow} Amount of pesticide removed in the flow (kg pst/ha)
$pst_{lat,ly}$ Pesticide removed in lateral flow from a layer (kg pst/ha)
pst'_{lat} Amount of lateral flow soluble pesticide generated in HRU on a given day (kg pst/ha)
$pst_{latstor,i-1}$ Lateral flow pesticide stored or lagged from the previous day (kg pst/ha)
$pst_{perc,ly}$ Pesticide moved to the underlying layer by percolation (kg pst/ha)
$pst_{s,ly}$ Amount of pesticide in the soil (kg pst/ha)
pst_{sed} Amount of sorbed pesticide transported to the main channel in surface runoff (kg pst/ha)
pst'_{sed} Sorbed pesticide loading generated in HRU on a given day (kg pst/ha)
$pst_{sedstor,i-1}$ Sorbed pesticide stored or lagged from the previous day (kg pst/ha)
pst_{sol} Solubility of the pesticide in water (mg/L)
pst_{surf} Pesticide removed in surface runoff (kg pst/ha)

pst'_{surf} Amount of surface runoff soluble pesticide generated in HRU on a given day (kg pst/ha)

$pst_{surstor,i-1}$ Surface runoff soluble pesticide stored or lagged from the previous day (kg pst/ha)

sed Sediment yield on a given day (metric tons)

$surlag$ Surface runoff lag coefficient

t_{conc} Time of concentration for a subbasin (hr)

w_{mobile} Amount of mobile water in the layer (mm H_2O)

$w_{perc,ly}$ Amount of water percolating to the underlying soil layer on a given day (mm H_2O)

β_{pst} Pesticide percolation coefficient

$\varepsilon_{pst:sed}$ Pesticide enrichment ratio

ρ_b Soil bulk density (Mg m^{-3})

ρ_w Density of water (1 Mg m^{-3})

15.6 REFERENCES

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CHAPTER 16

EQUATIONS: WATER QUALITY PARAMETERS

In addition to sediment, nutrients and pesticides, SWAT calculates the amount of algae, dissolved oxygen and carbonaceous biological oxygen demand (CBOD) entering the main channel with surface runoff. Loadings of these three parameters are required to monitor the quality of stream water. This chapter reviews the algorithms governing movement of algae, dissolved oxygen and CBOD from land areas to the stream network.

16.1 ALGAE

Suspended algal biomass is assumed to be directly proportional to chlorophyll *a*. Therefore, the algal biomass loading to the stream can be estimated as the chlorophyll *a* loading from the land area. Cluis et al. (1988) developed a relationships between the nutrient enrichment index (total N: total P), chlorophyll *a*, and algal growth potential in the North Yamaska River, Canada.

$$(AGP + chla) \cdot v_{surf} = f \cdot \left(\frac{TN}{TP}\right)^g \qquad\qquad 16.1.1$$

where *AGP* is the algal growth potential (mg/L), *chla* is the chlorophyll *a* concentration in the surface runoff (μg/L), v_{surf} is the surface runoff flow rate (m³/s), *TN* is the total Kjeldahl nitrogen load (kmoles), *TP* is the total phosphorus load (kmoles), *f* is a coefficient and *g* is an exponent.

The chlorophyll *a* concentration in surface runoff is calculated in SWAT using a simplified version of Cluis et al.'s exponential function (1988):

$$chla = 0 \qquad\qquad \text{if } (v_{surf} < 10^{-5} \text{ m}^3/\text{s}) \text{ or } (TP \text{ and } TN < 10^{-6}) \qquad 16.1.2$$

$$chla = \frac{0.5 \cdot 10^{2.7}}{v_{surf}} \qquad \text{if } v_{surf} > 10^{-5} \text{ m}^3/\text{s}, \text{ and } (TP \text{ and } TN > 10^{-6}) \qquad 16.1.3$$

$$chla = \frac{0.5 \cdot 10^{0.5}}{v_{surf}} \qquad \text{if } v_{surf} > 10^{-5} \text{ m}^3/\text{s}, TP < 10^{-6} \text{ and } TN > 10^{-6} \qquad 16.1.4$$

16.2 CARBONACEOUS BIOLOGICAL OXYGEN DEMAND

Carbonaceous biological oxygen demand (CBOD) defines the amount of oxygen required to decompose the organic matter transported in surface runoff. The SWAT loading function for the ultimate CBOD is based on a relationship given by Thomann and Mueller (1987):

$$cbod_{surq} = \frac{2.7 \cdot orgC_{surq}}{Q_{surf} \cdot area_{hru}} \qquad\qquad 16.2.1$$

where $cbod_{surq}$ is the CBOD concentration in surface runoff (mg CBOD/L), $orgC_{surq}$ is the organic carbon in surface runoff (kg orgC), Q_{surf} is the surface runoff on a given day (mm H$_2$O), and $area_{hru}$ is the area of the HRU (km^2).

The amount of organic carbon in surface runoff is calculated:

$$orgC_{surq} = 1000 \cdot \frac{orgC_{surf}}{100} \cdot sed \cdot \varepsilon_{C:sed} \qquad\qquad 16.2.2$$

where $orgC_{surq}$ is the organic carbon in surface runoff (kg orgC), $orgC_{surf}$ is the percent organic carbon in the top 10 mm of soil (%), sed is the sediment loading from the HRU (metric tons), and $\varepsilon_{C:sed}$ is the carbon enrichment ratio.

16.2.1 ENRICHMENT RATIO

As surface runoff flows over the soil surface, part of the water's energy is used to pick up and transport soil particles. The smaller particles weigh less and are more easily transported than coarser particles. When the particle size distribution of the transported sediment is compared to that of the soil surface layer, the sediment load to the main channel has a greater proportion of clay sized particles. In other words, the sediment load is enriched in clay particles. Organic carbon in the soil is attached primarily to colloidal (clay) particles, so the sediment load will also contain a greater proportion or concentration of organic carbon than that found in the soil surface layer.

The enrichment ratio is defined as the ratio of the concentration of organic carbon transported with the sediment to the concentration in the soil surface layer. SWAT will calculate an enrichment ratio for each storm event. To calculate the enrichment ratio, SWAT uses a relationship described by Menzel (1980) in which the enrichment ratio is logarithmically related to sediment concentration. The equation used to calculate the carbon enrichment ratio, $\varepsilon_{C:sed}$, for each storm event is:

$$\varepsilon_{C:sed} = 0.78 \cdot \left(conc_{sed,surq}\right)^{-0.2468} \qquad\qquad 16.2.3$$

where $conc_{sed,surq}$ is the concentration of sediment in surface runoff (Mg sed/m^3 H$_2$O). The concentration of sediment in surface runoff is calculated:

$$conc_{sed,surq} = \frac{sed}{10 \cdot area_{hru} \cdot Q_{surf}}$$ 16.2.4

where *sed* is the sediment yield on a given day (metric tons), $area_{hru}$ is the HRU area (ha), and Q_{surf} is the amount of surface runoff on a given day (mm H_2O).

Table 16-1: SWAT input variables that pertain to CBOD in surface runoff.

Variable Name	Definition	Input File
SOL_CBN	$orgC_{ly}$: Percent organic carbon in the top 10 mm of soil (%)	.sol

16.3 DISSOLVED OXYGEN

Rainfall is assumed to be saturated with oxygen. To determine the dissolved oxygen concentration of surface runoff, the oxygen uptake by the oxygen demanding substance in runoff is subtracted from the saturation oxygen concentration.

$$Ox_{surf} = Ox_{sat} - \kappa_1 \cdot cbod_{surq} \cdot \frac{t_{ov}}{24}$$ 16.3.1

where Ox_{surf} is the dissolved oxygen concentration in surface runoff (mg O_2/L), Ox_{sat} is the saturation oxygen concentration (mg O_2/L), κ_1 is the CBOD deoxygenation rate (day^{-1}), $cbod_{surq}$ is the CBOD concentration in surface runoff (mg CBOD/L), and t_{ov} is the time of concentration for overland flow (hr). For loadings from HRUs, SWAT assumes $\kappa_1 = 1.047$ day^{-1}.

16.3.1 OXYGEN SATURATION CONCENTRATION

The amount of oxygen that can be dissolved in water is a function of temperature, concentration of dissolved solids, and atmospheric pressure. An equation developed by APHA (1985) is used to calculate the saturation concentration of dissolved oxygen:

$$Ox_{sat} = \exp\left[-139.34410 + \frac{1.575701 \times 10^5}{T_{wat,K}} - \frac{6.642308 \times 10^7}{\left(T_{wat,K}\right)^2} \right.$$

$$\left. + \frac{1.243800 \times 10^{10}}{\left(T_{wat,K}\right)^3} - \frac{8.621949 \times 10^{11}}{\left(T_{wat,K}\right)^4} \right]$$ 16.3.2

where Ox_{sat} is the equilibrium saturation oxygen concentration at 1.00 atm (mg O_2/L), and $T_{wat,K}$ is the water temperature in Kelvin (273.15+°C).

16.4 NOMENCLATURE

AGP Algal growth potential (mg/L)
Ox_{sat} Saturation oxygen concentration (mg O_2/L)
Ox_{surf} Dissolved oxygen concentration in surface runoff (mg O_2/L)
Q_{surf} Surface runoff on a given day (mm H_2O)
$T_{wat,K}$ Water temperature in Kelvin (273.15+°C)
TN Total Kjeldahl nitrogen load (moles)
TP Total phosphorus load (moles)

$area_{hru}$ Area of the HRU (km^2)
$cbod_{surq}$ CBOD concentration in surface runoff (mg CBOD/L)
$chla$ Chlorophyll a concentration in the surface runoff (µg/L)
$conc_{sed,surq}$ Concentration of sediment in surface runoff (Mg sed/m^3 H_2O)
f Coefficient
g Exponent
$orgC_{surf}$ Percent organic carbon in the top 10 mm of soil (%)
$orgC_{surq}$ Organic carbon in surface runoff (kg orgC),
sed Sediment loading from the HRU (metric tons)
t_{ov} Time of concentration for overland flow (hr)
v_{surf} Surface runoff flow rate (m^3/s)

$\varepsilon_{C:sed}$ Carbon enrichment ratio
κ_1 CBOD deoxygenation rate (day^{-1})

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